Multi-Attribute Tradespace Exploration with Concurrent Design:

Project X-TOS

Adam Ross, MIT SSPARC

Contributors: Nathan P. Diller, Professor Daniel Hastings

New Design Paradigms Workshop

June 26, 2002

Outline

- Motivation
- MATE-CON definitions
- MATE-CON process
- X-TOS
  - Problem outline
  - MATE-CON application (process and results)
- MATE-CON Benefits
  - Delivery of value-centric design (utility as metric)
  - Knowledge of global tradespace (many d.v. → attributes computed)
  - Flexibility to changing preferences
  - Rapid exploration (several mins to several hrs)
  - Optimizable process (DSM analysis)

Motivation

Issues raised in research of space system design and development

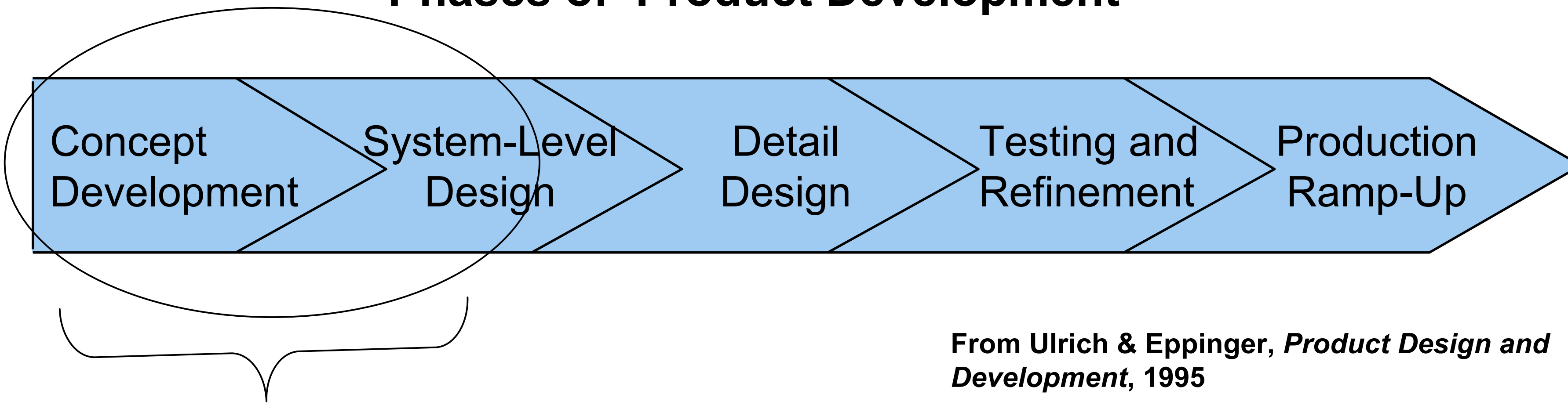
- Cost committal at beginning of design process
  – Need for front-end attention
- Long iteration times
- Communication bottlenecks
- Advances in the theory of product development processes
  – Need to streamline process
- Lack of "systems thinking"
- Growing complexity of systems
  – Need for including important stakeholders
  – Need for focusing on system-level interactions

Some Important Definitions

- Attribute: a decision maker-perceived metric that measures how well a decision maker-defined objective is met
- Utility: a dimensionless parameter that measures the “perceived value under uncertainty” of an attribute
- Design variable: a designer-controlled quantitative parameter that reflects an aspect of a concept
- Design vector: a set of design variables that taken together uniquely define a design or architecture

MATE-CON: System Definition

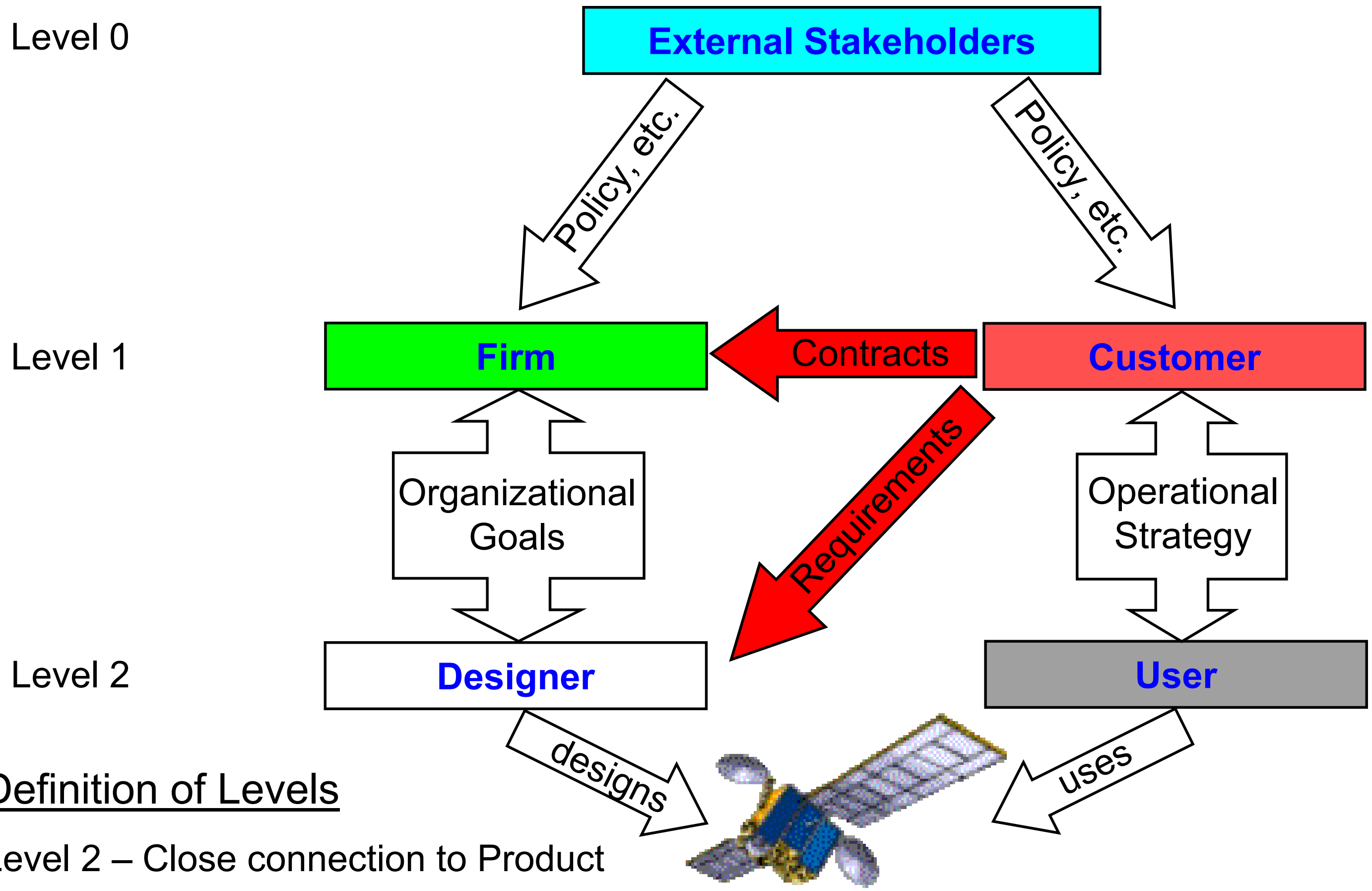
Phases of Product Development



From Ulrich & Eppinger, *Product Design and Development*, 1995

MATE-CON Process

Architecture-level Dec. Makers



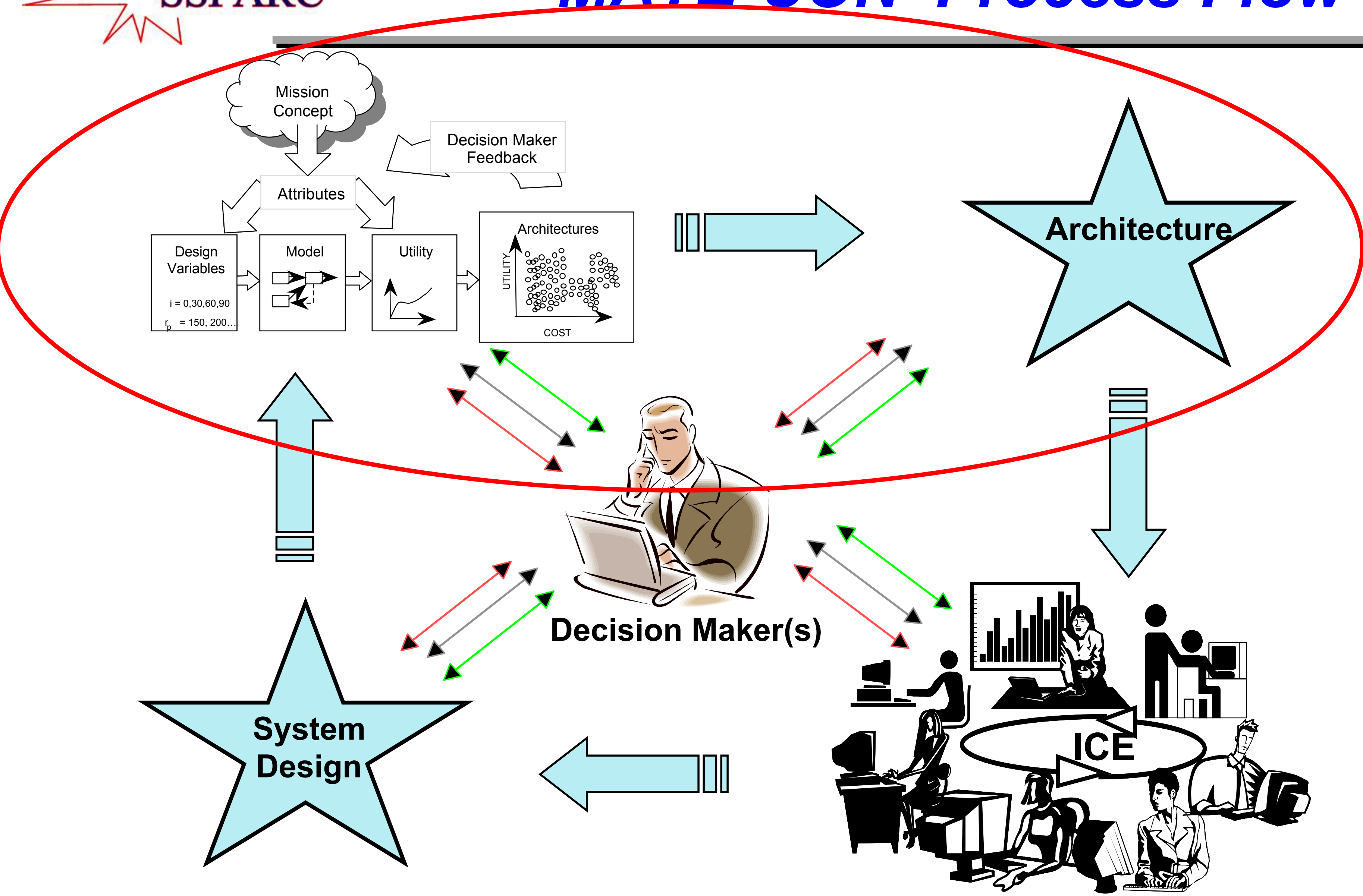
Definition of Levels

Level 2 – Close connection to Product

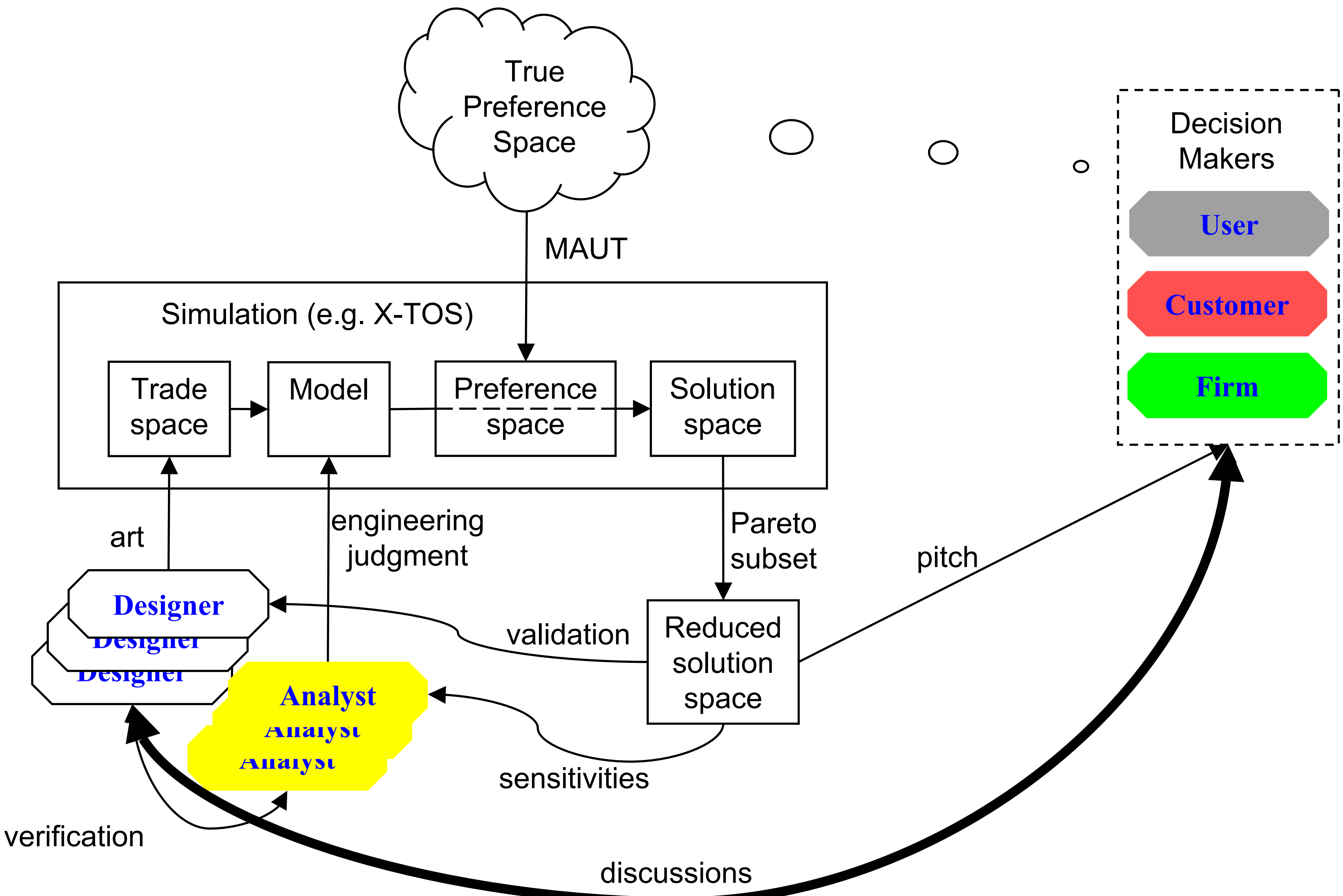
Level 1 – Distant connection to Product

Level 0 – Little or no connection to Product

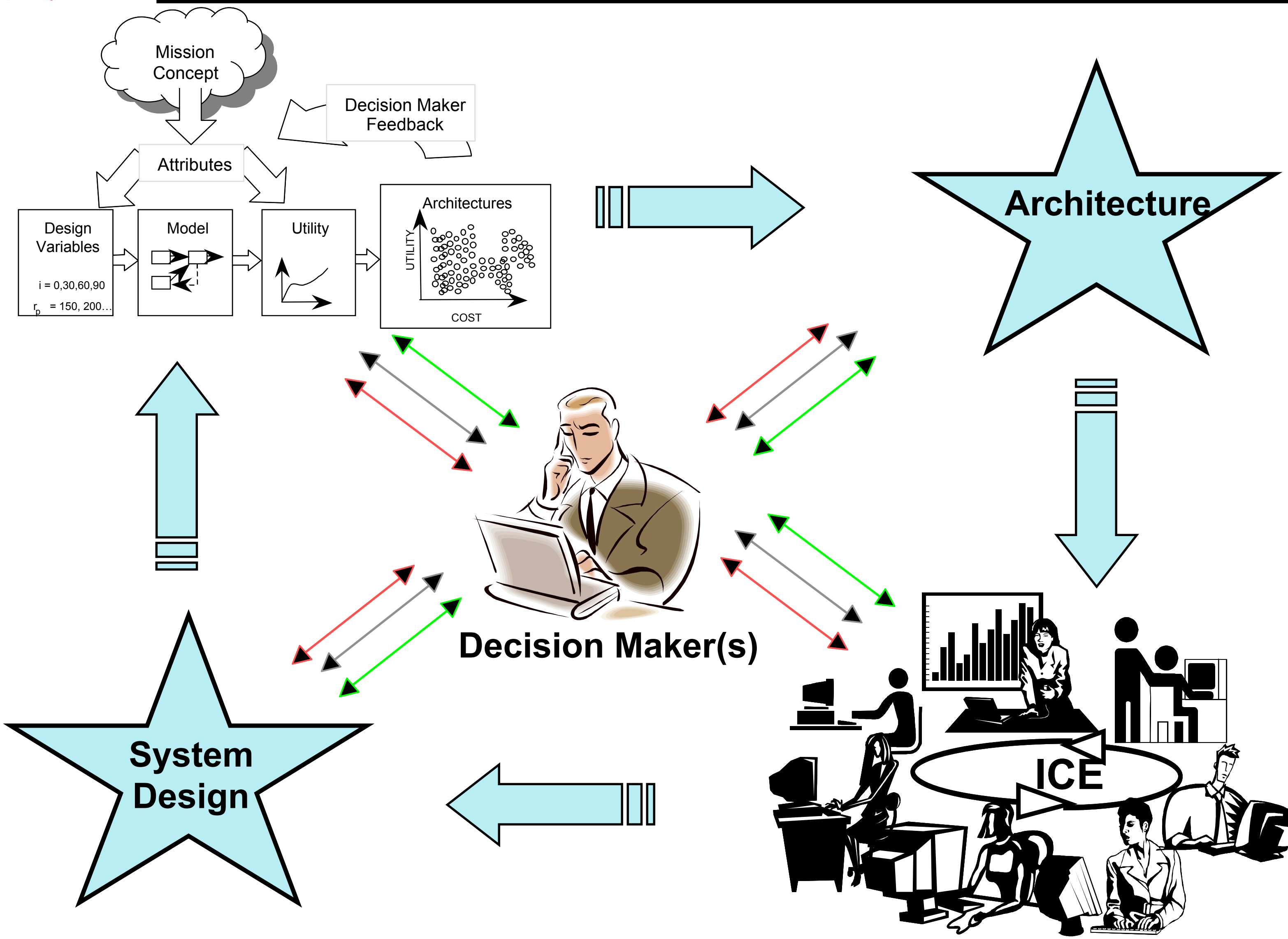
MATE-CON Process Flow



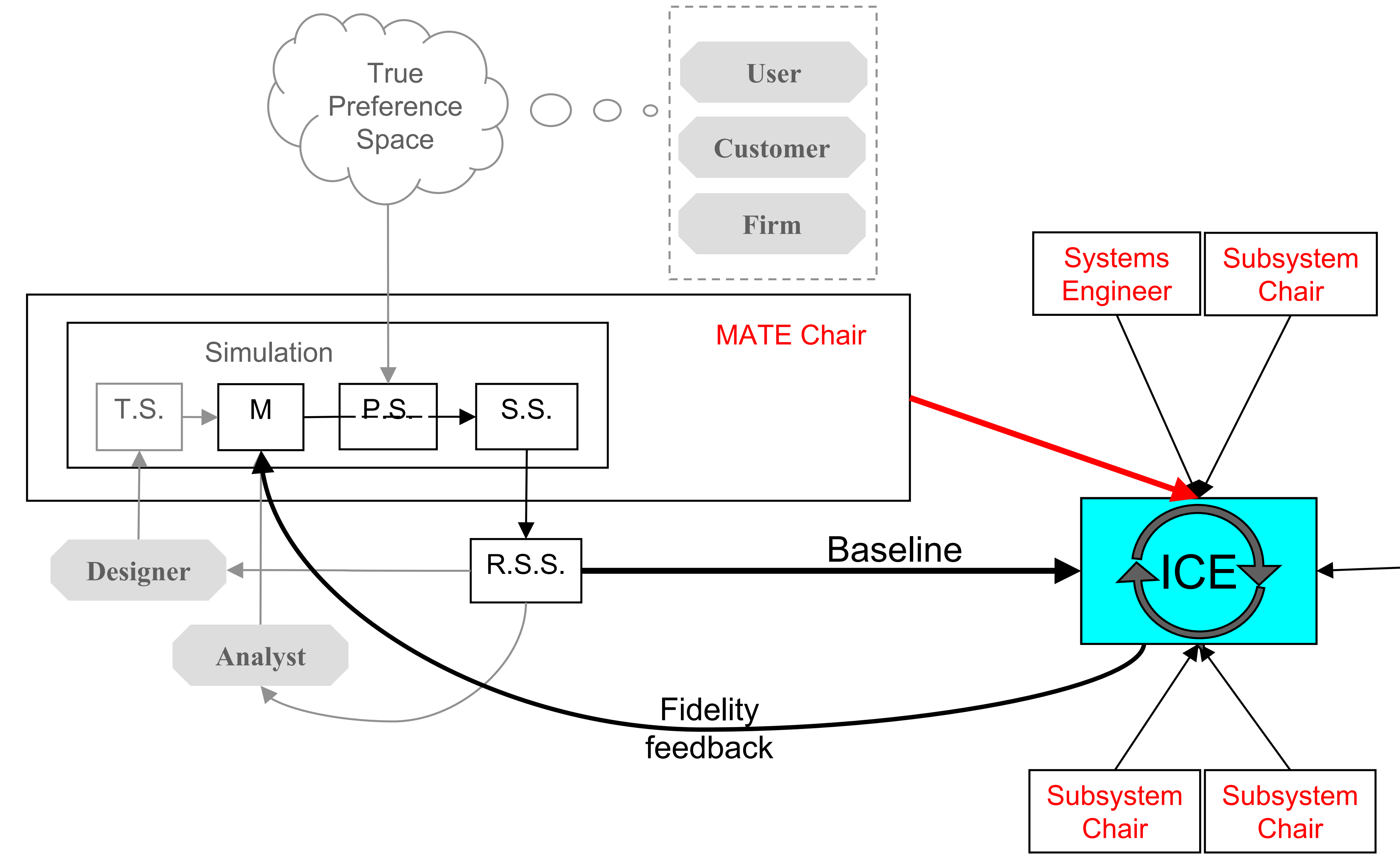
MATE Role Interactions pre-ICE



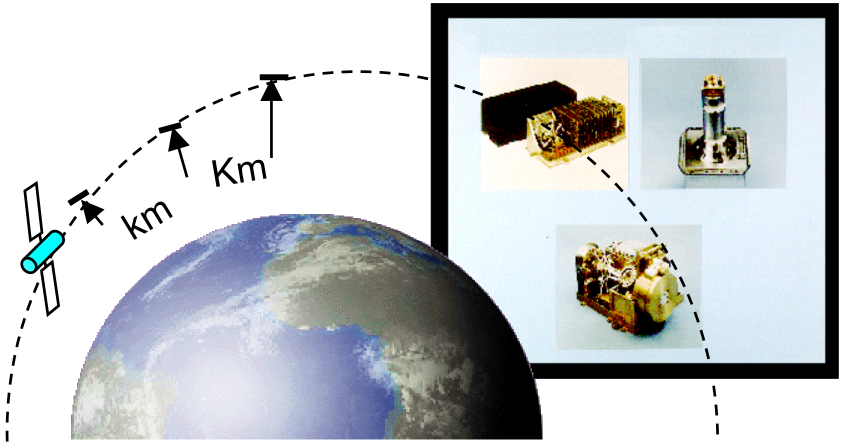
MATE-CON Process Flow

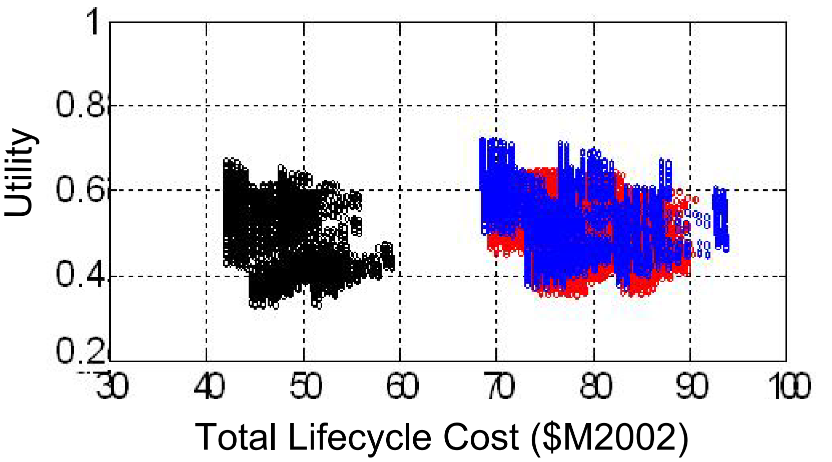


MATE Process with ICE



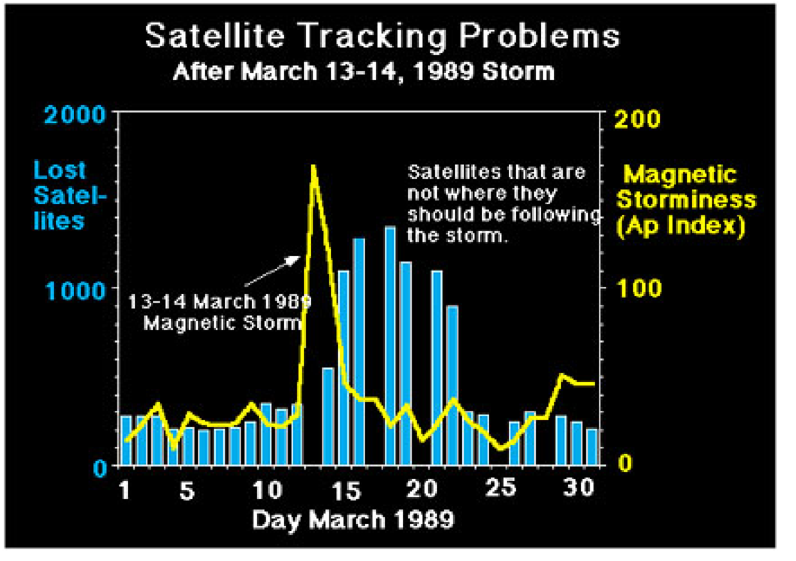
Project 4: X-TOS





DESIGN VARIABLES

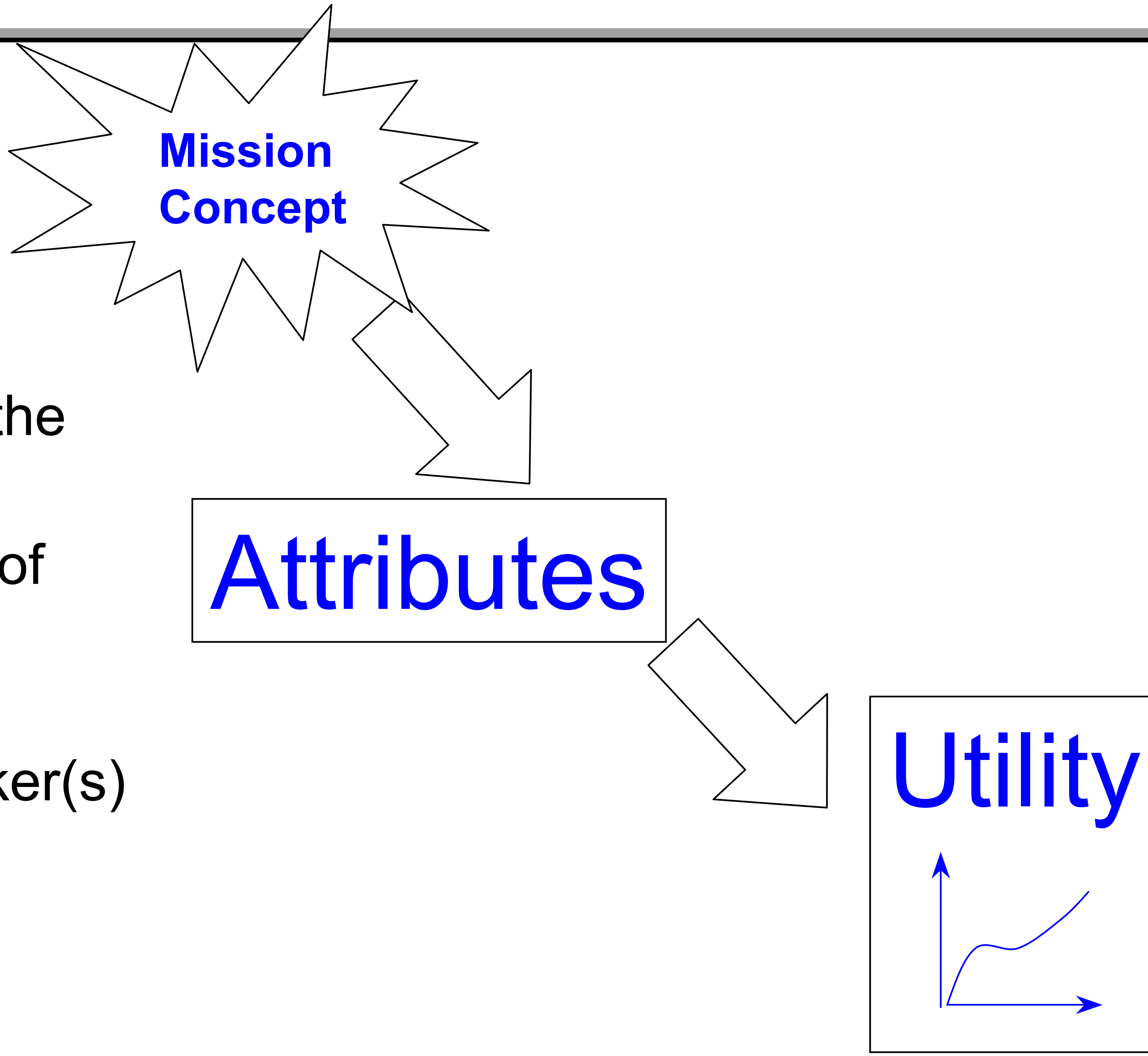
- Mission Scenarios
  - Single satellite, single launch
  - Two satellites, sequential launch
  - Two satellites, parallel
- Orbital Parameters
  - Apogee altitude (km) 150-1100
  - Perigee altitude (km) 150-1100
  - Orbit inclination 0, 30, 60, 90
- Physical Spacecraft Parameters
  - Antenna gain
  - communication architecture
  - propulsion type
  - power type
  - delta_v



Number of Architectures Explored: 50488

SSPARC

Define the Mission



- Understand the mission
- Create a list of attributes
- Interview the decision maker(s)
- Create utility curves

Attributes as Decision Metrics

- Quantifiable variable capable of measuring how well a *decision maker-defined* objective is met
- Set of attributes must be:
  - Complete
  - Operational
  - Decomposable
  - Non-redundant
  - Minimal
  - Perceived Independent*
- "Rule of 7": Human mind limited to roughly 7 simultaneous concepts

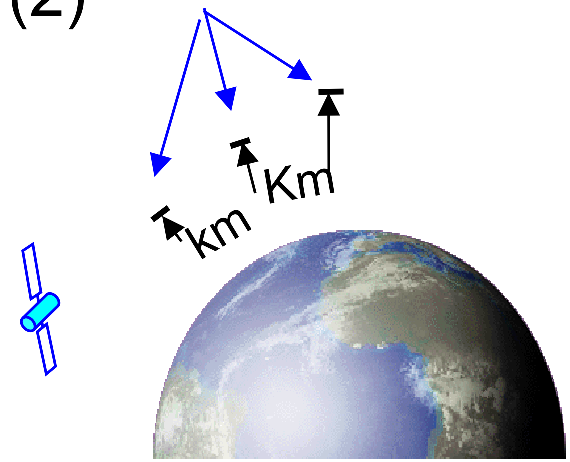
*Not strictly necessary, but reduces interview time and complexity.

X-TOS User Attributes

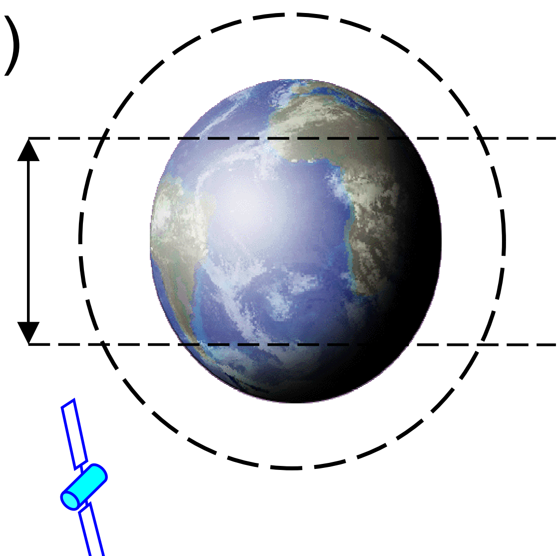
1) Data Life Span
2) Data Altitude
3) Maximum Latitude
4) Time Spent at Equator
5) Data Latency

(1)

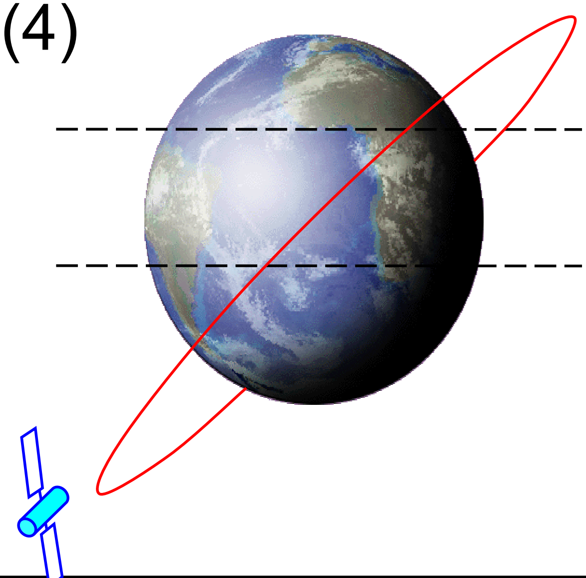
(2)



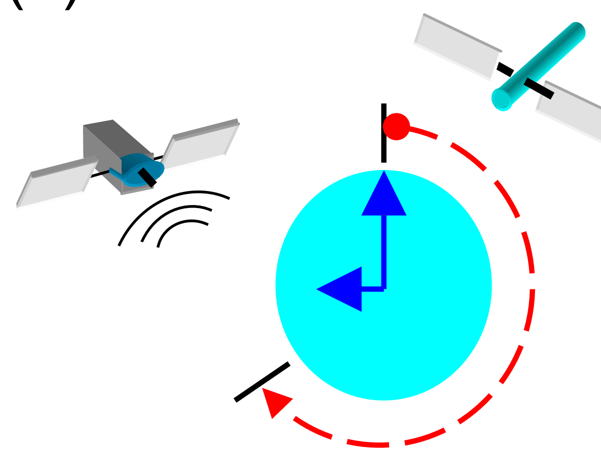
(3)



(4)

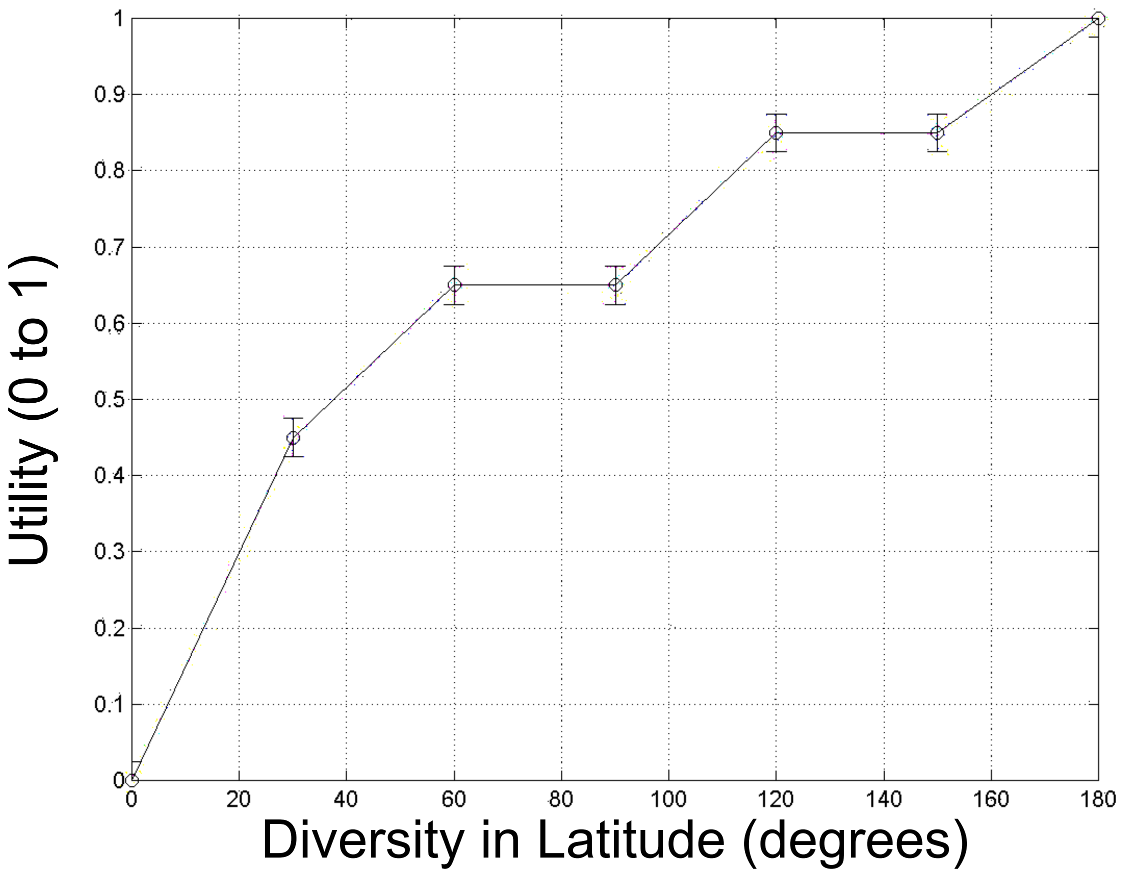


(5)



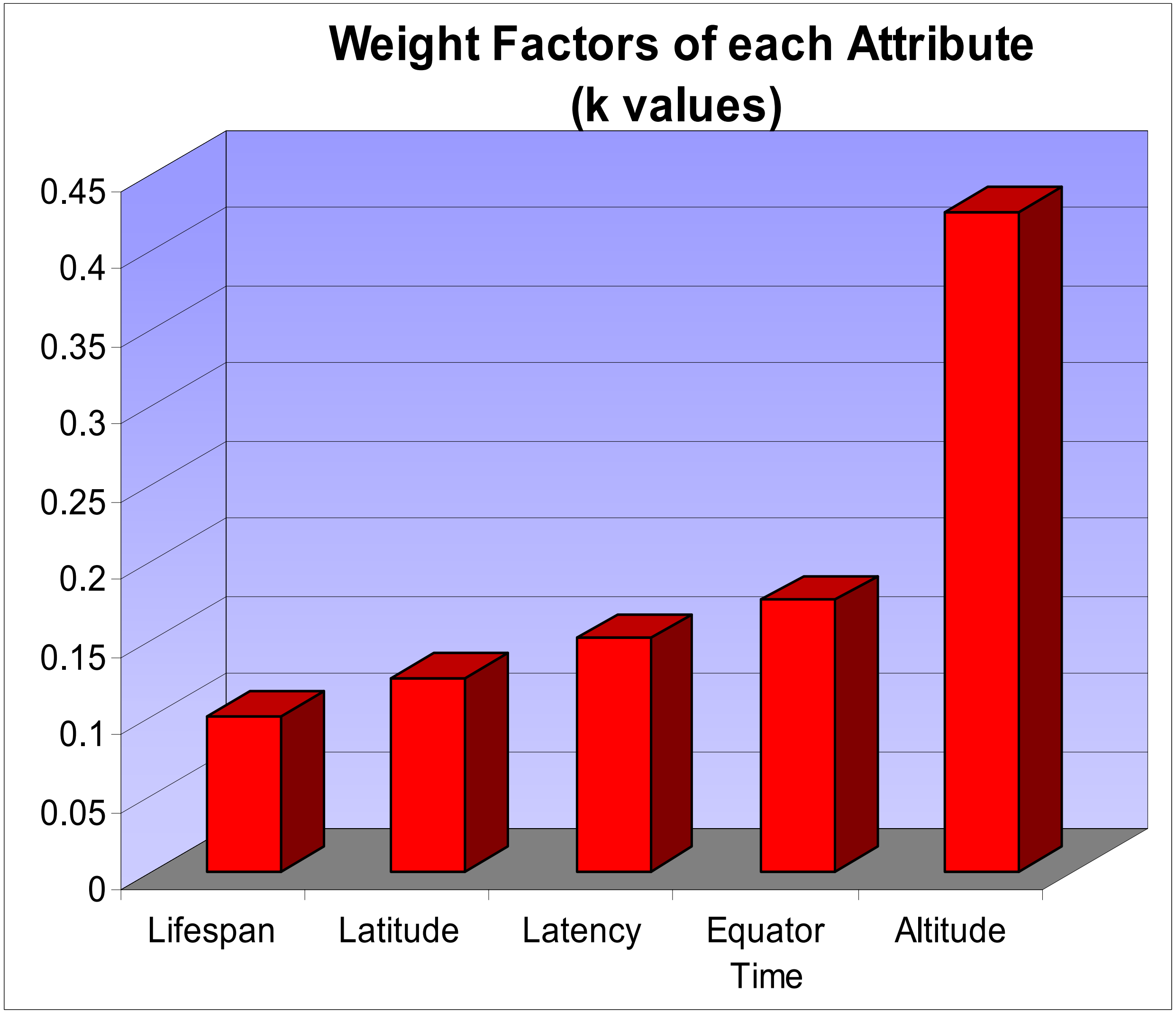
Single Attribute Utility

- Mapping of attributes to perceived-value under uncertainty
- Utility is an ordered metric scale (e.g. °F)
- Not required to have "analytic" form

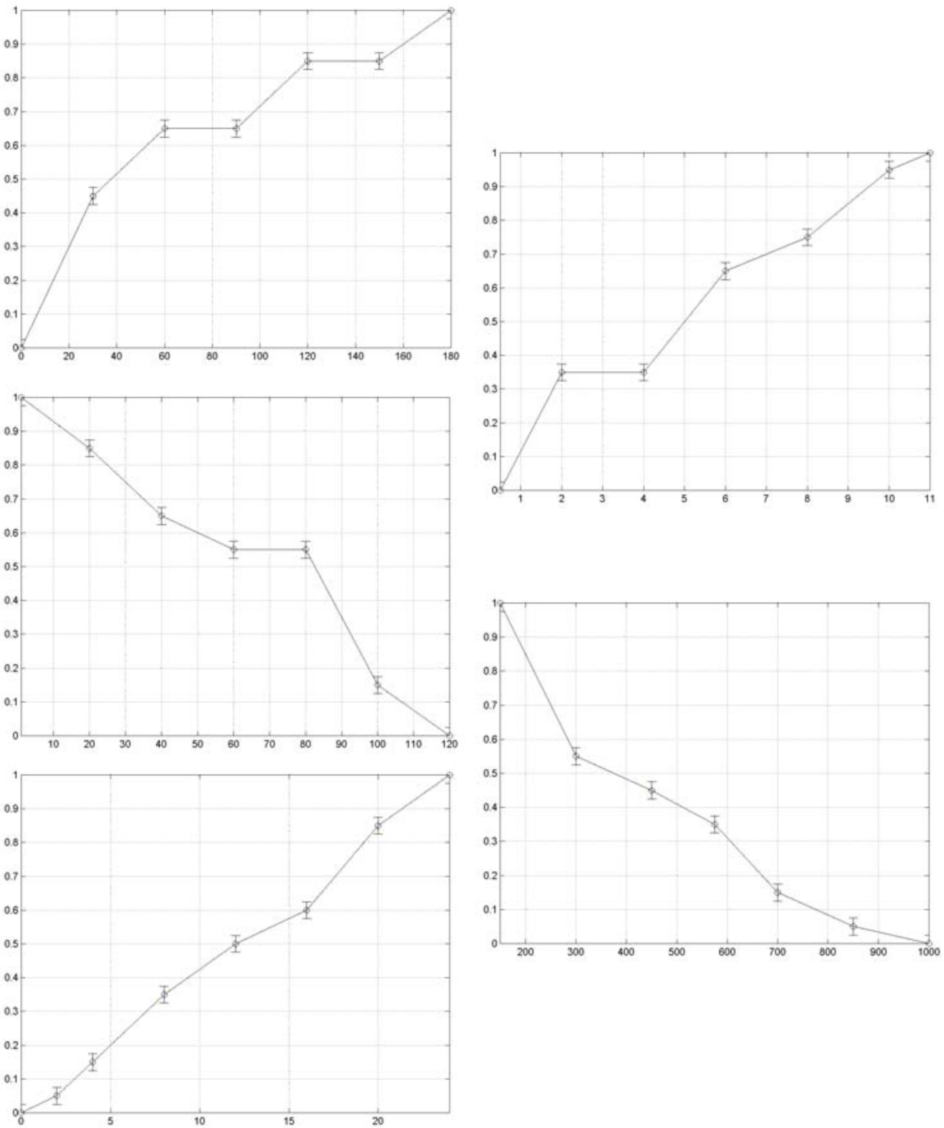


Single Attributes Aggregated

- Depicts the relative importance of each attribute to the decision maker
- Resolution of ±0.025
- User interviewed for ~2 hours



Multi-Attribute Utility Function*

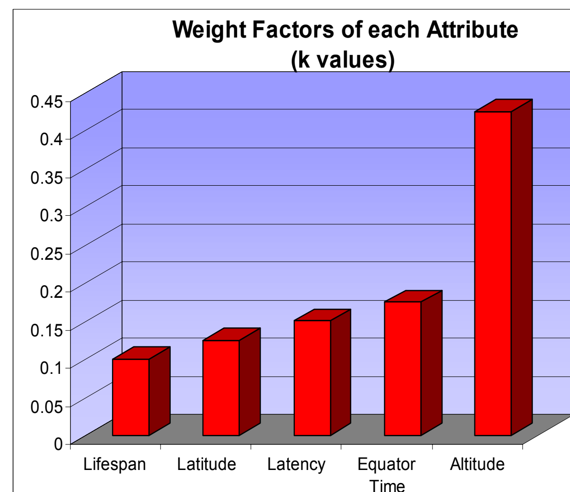


Single attribute utility

$$KU(\underline{X})+1=\prod_{i=1}^{N}\left(Kk_iU(X_i)+1\right)$$

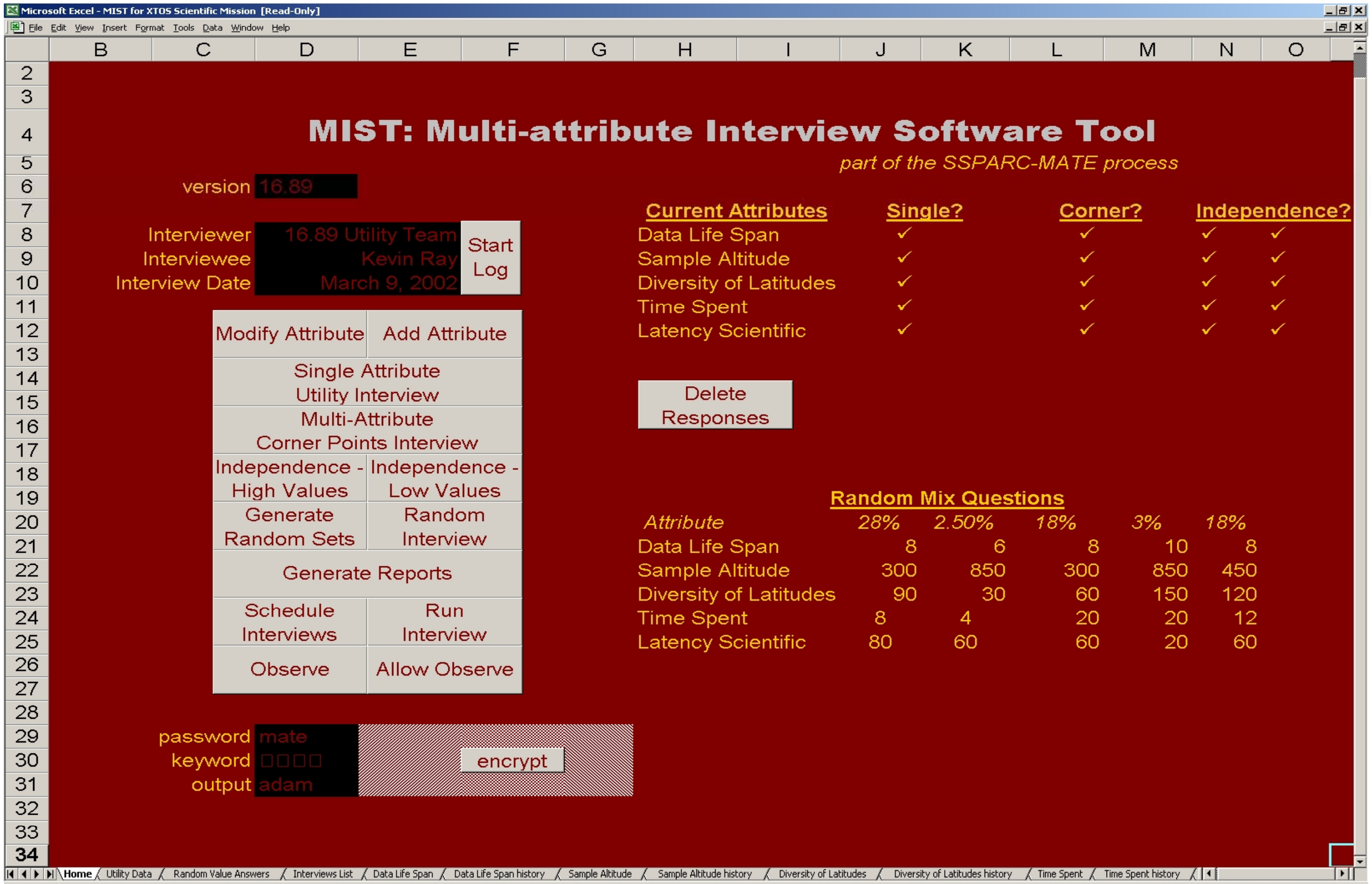
Normalization constant

Relative “weight”



*Keeney & Raiffa, 1976.

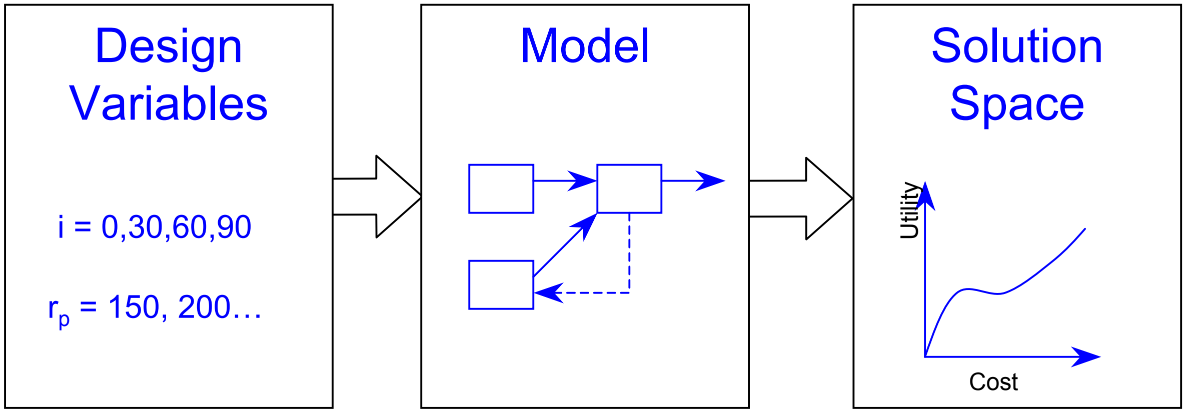
Utility Interview Software (MIST)



Interviews require interaction with decision makers to determine utility functions

*MIST created by Satwik Seshasai, MIT 2002

Explore the Tradespace

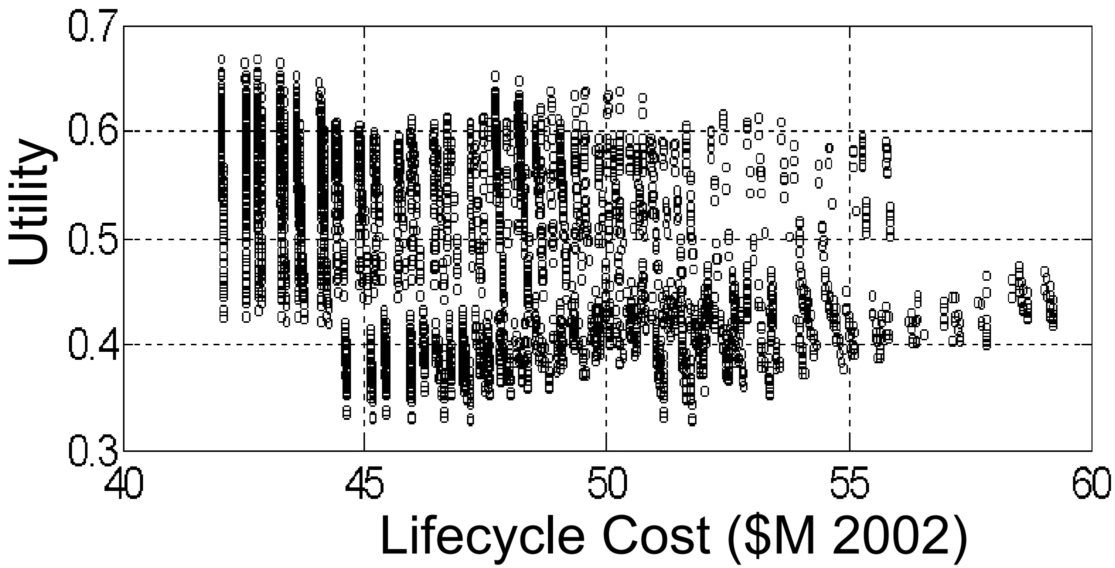


- Create design vector
- Create model and simulation software
- Find utilities / analyze architectures

X-TOS Design Vector

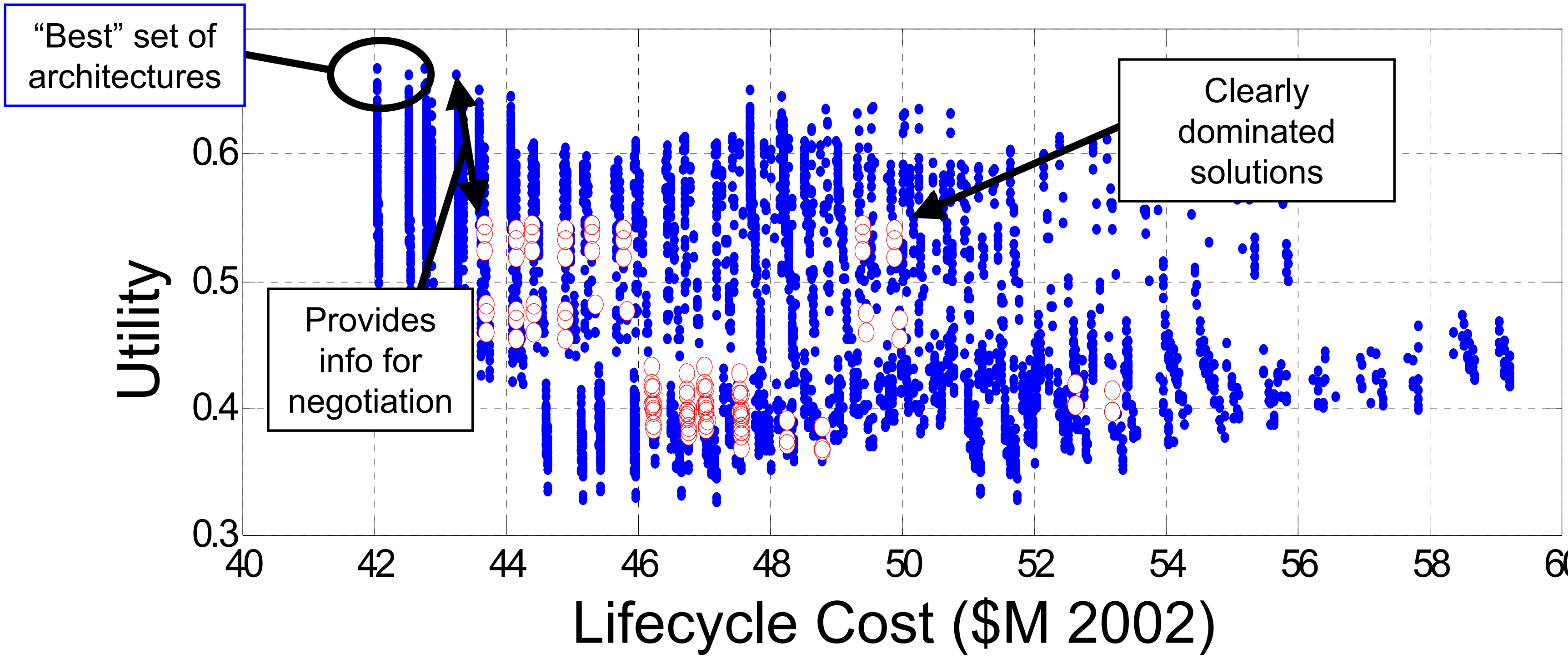
Variable:	First Order Effect:
Mission Scenarios:	
•Single satellite, single launch	Cost
•Two satellites, sequential launch	Life span, Cost
•Two satellites, parallel launch	Latitude Range, Time at Equator, Cost
Orbital Parameters:	
•Apogee altitude (200 to 2000 km)	Life span, Altitude
•Perigee altitude (150 to 350 km)	Life span, Altitude
•Orbit inclination (0 to 90 degrees)	Life span, Altitude, Latitude Range, Time at Equator
Physical Spacecraft Parameters:	
•Antenna gain (low/high)	Latency
•Comm Architecture (TDRSS/AFSCN)	Latency
•Propulsion type (Hall/Chemical)	Life span
•Power type (fuel/solar)	Life span
•Total ΔV capability (200 to 1000 m/s)	Life span

Initial Solution Space (X-TOS)



- Examine Utility vs. Cost plot
- Explore results with decision maker(s). Revise utility if necessary and rerun architecture space
- Select initial design point(s) for further evaluation

STEP 1 Possible Results



Blue points represent X-TOS initial tradespace exploration

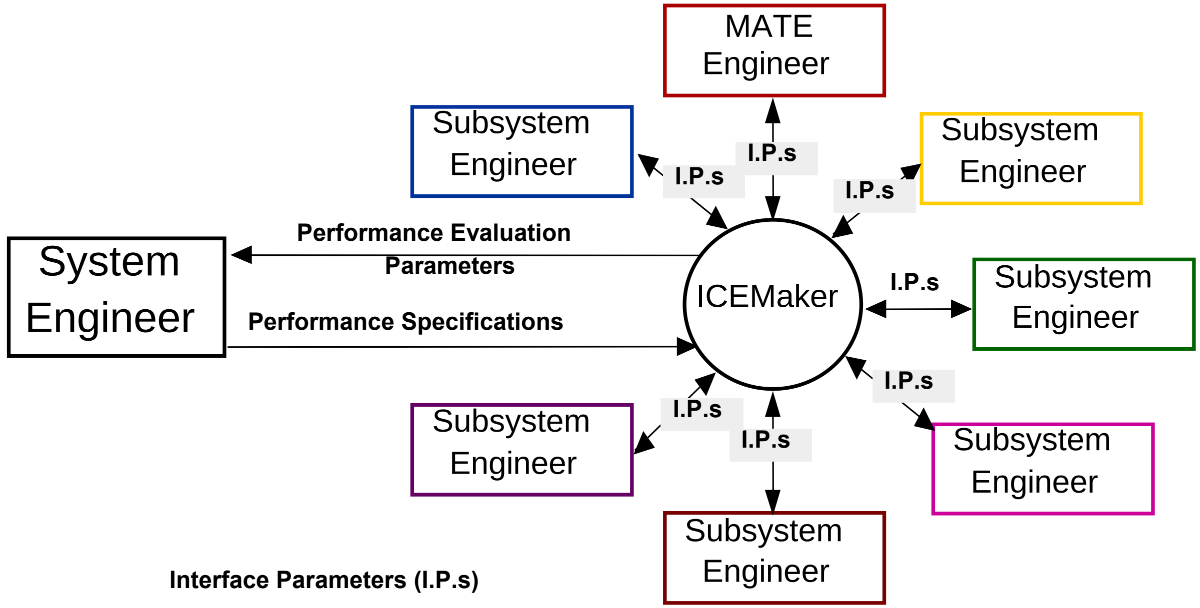
Red points represent possible STEP 1 equivalent architectures

<u>Important</u>: Convert points back to attribute values for communication

STEP 1 mission is X-TOS precursor flown in early 1990s

Flow Selected Design Point(s)

ICE Subsystem Engineers represent downstream business units to achieve enterprise buy-in (e.g. manufacturing)

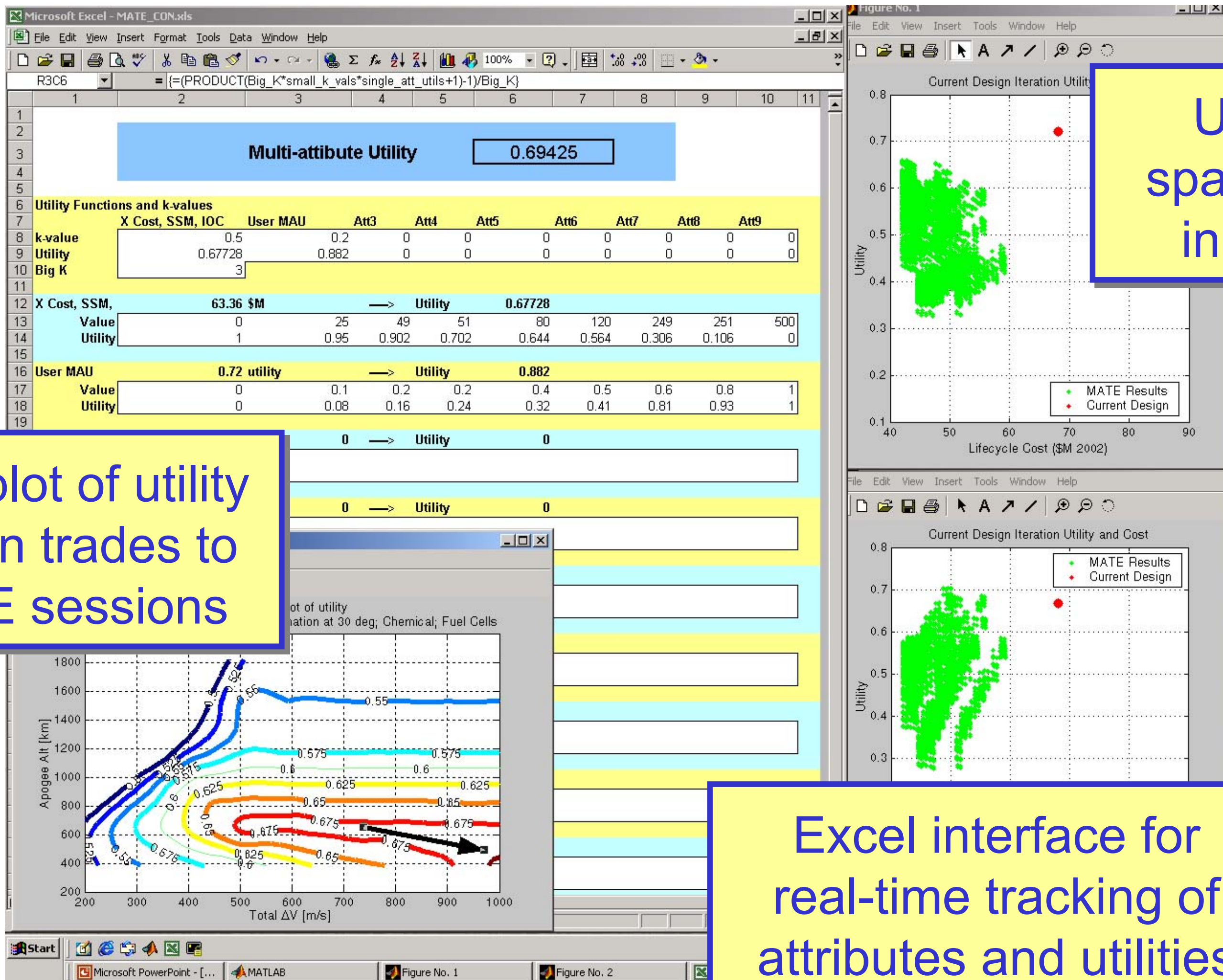


- Repeat modeling with increased fidelity (ICE)
- Repeat utility calculations with improved fidelity designs to revise trade space

Architecture-level selected point design(s) flow down to Integrated Concurrent Engineering environment

* ICEMaker courtesy of Dr. Joel Sercel, Caltech

MATE-CON Chair Motivates ICE



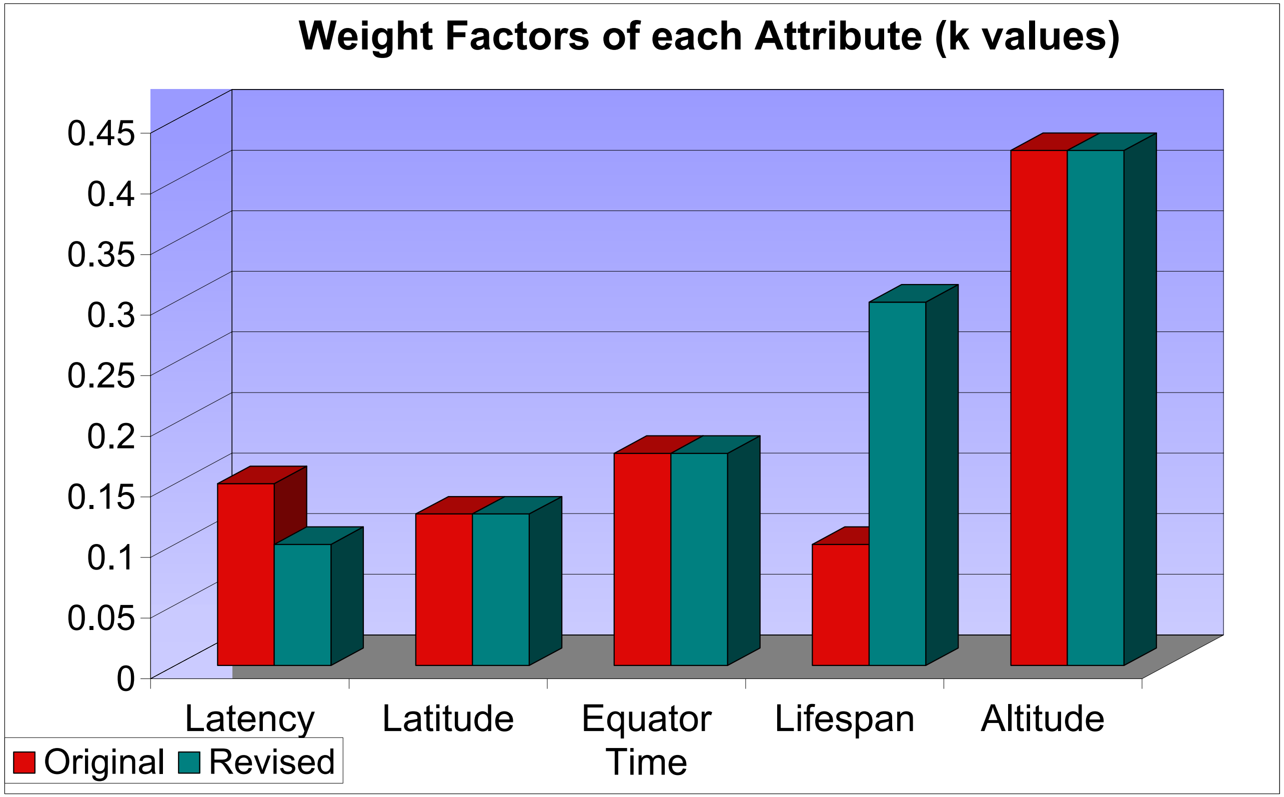
Utility-cost spaces plotted in MATLAB

Contour plot of utility vs. design trades to guide CE sessions

Excel interface for real-time tracking of attributes and utilities

Nathan Diller, Thesis, MIT 2002

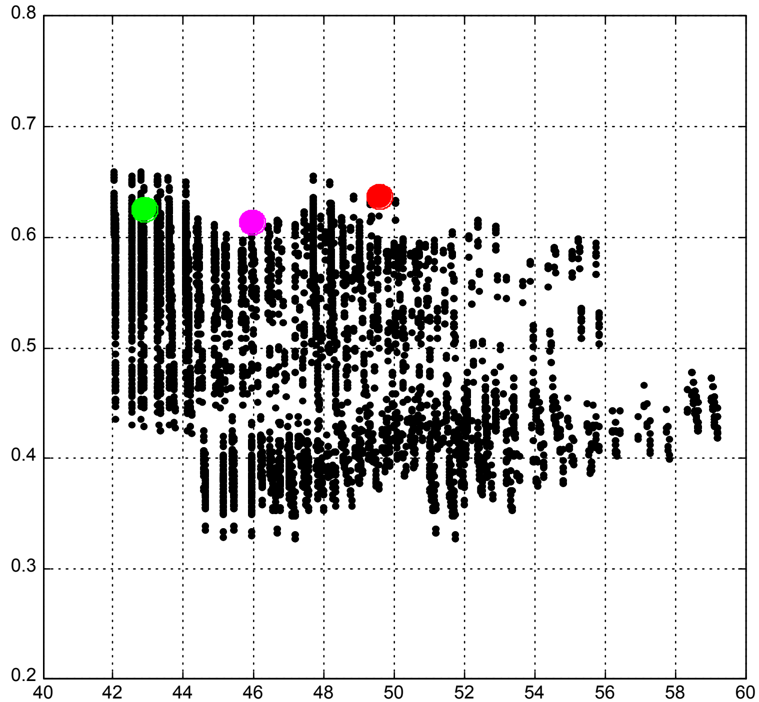
Preference Change Flexibility



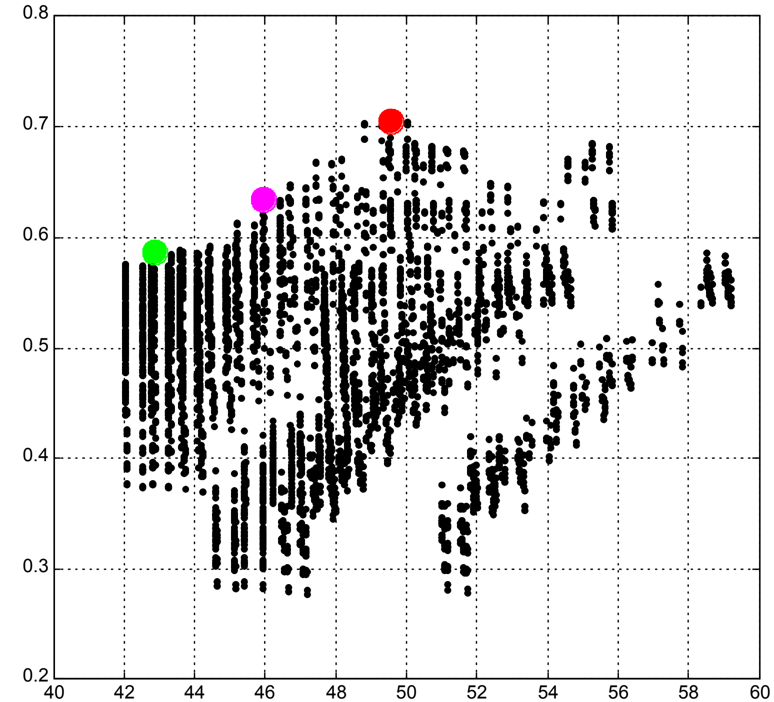
- After reviewing MATE results, User expressed revised preferences
- Increased importance of Lifespan
- Slight decrease in importance of Latency

Rapid Tradespace Re-evaluation

Original



Revised



Preference change: Lifespan (increased), Latency (decreased)

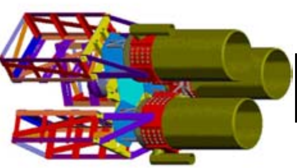
Re-evaluation time: several minutes to several hours

SSPARC

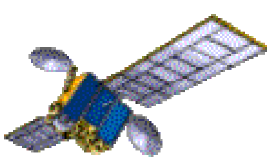
MATE Process Formalization

Need Identification — Identify, Need, Mission, Scope

Architecture Solution Exploration — Define Design Space and Preference Space; Model System

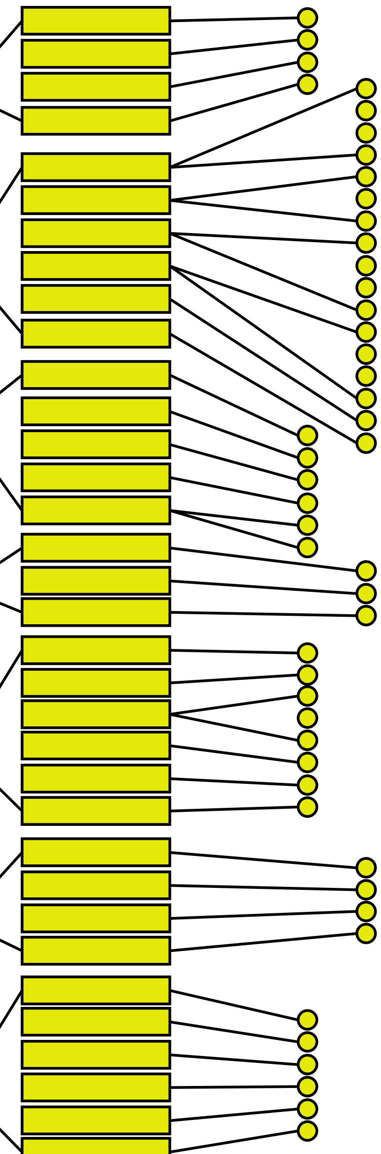


Architecture Evaluation — Simulate System; Analyze System

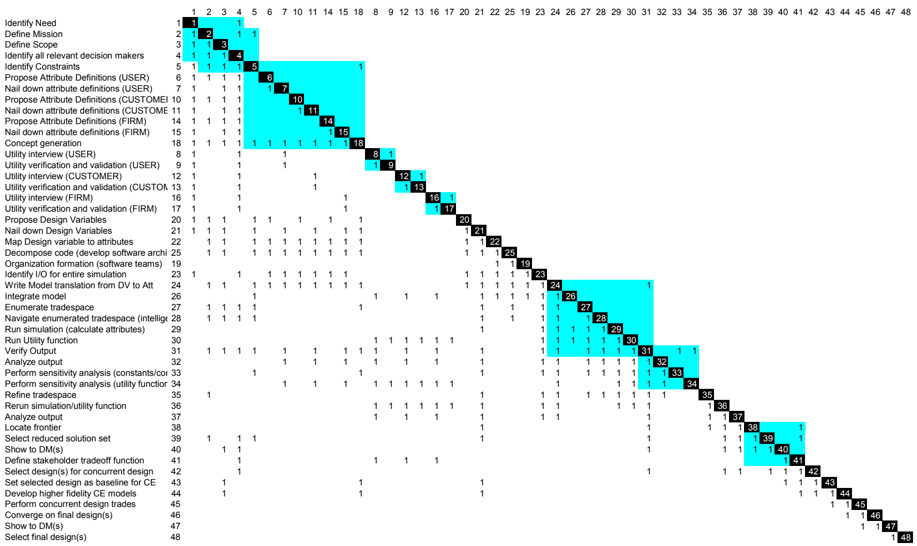


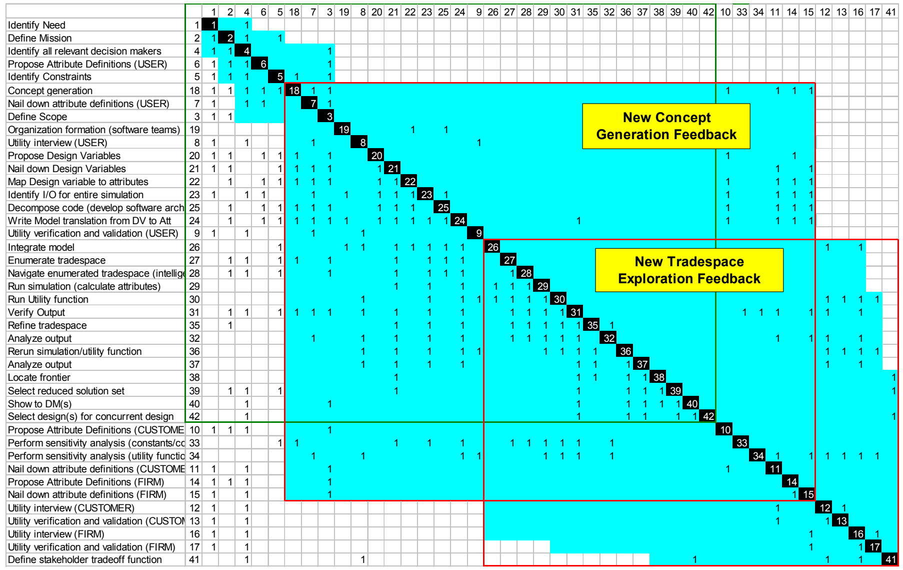
Design Solution Exploration — Select Reduced Solution Space

Design Evaluation — Concurrent Design



MATE Process Analyses



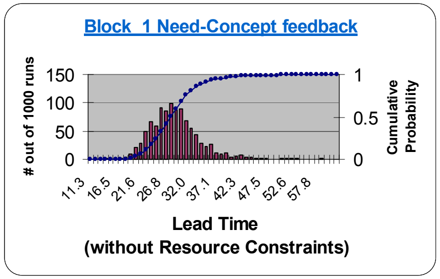


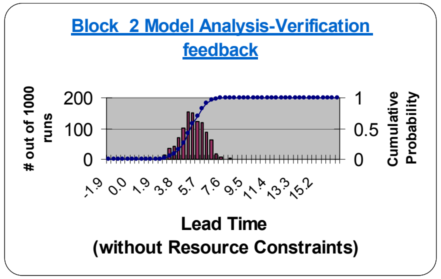
Optimized

Actual X-TOS

Highlighted boxes indicate feedback blocks

X-TOS “completed” in one semester.





Activity representation allows for streamlined process modeling

MATE-CON Benefits

- Preference captured through utility
  - Reduces miscommunication of upstream needs
  - Focuses design to achieve better “value”
- Modular model-based design linked with ICE
  - Allows incremental improvement in fidelity
  - Enables large tradespace exploration
  - Achieves buy-in and input from downstream stakeholders
- Formal process developed through activity list
  - Allows process optimization and analysis
  - Enables better allocation of designer resources

Backup Slides

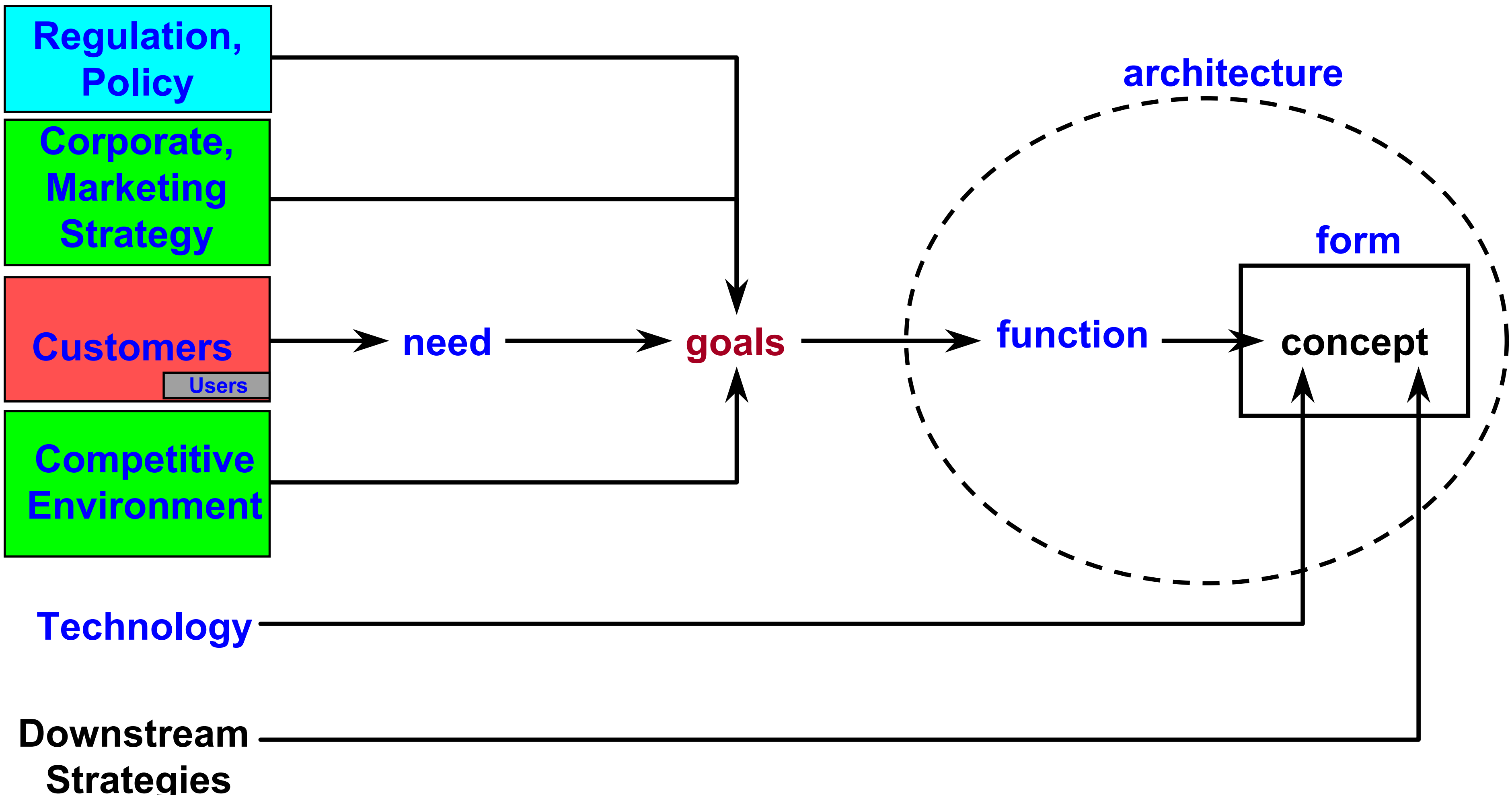
Abstract

- MIT is developing a design process that incorporates Multi-Attribute Utility Theory with model, simulation-based and concurrent design to enable a more flexible and rapid exploration of space system tradespaces. A formal framework for rapid communication of preferences promises to reduce cycle time and result in a higher value product.

Further Definitions

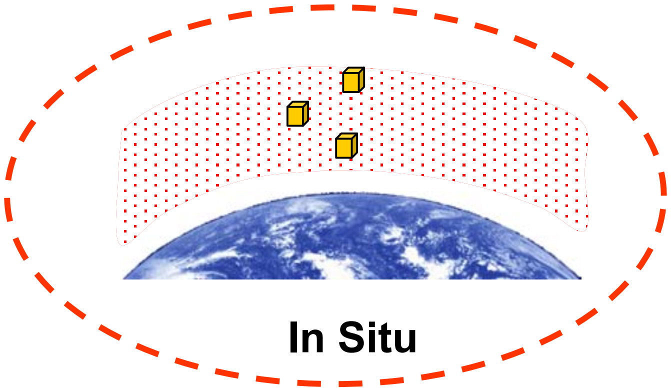
- Tradespace: the space spanned by the enumerated design variables; the potential solution space
- Exploration: the utility-guided search for better solutions within a tradespace
- Decision maker: those roles that make decisions that impact a system at any stage of its lifecycle
- Pareto frontier: the economically efficient allocation of resources that requires making one factor worse in order to improve another

Upstream Influences on Architecture



Source: Crawley & de Weck, System Architecture 16.882, 2001

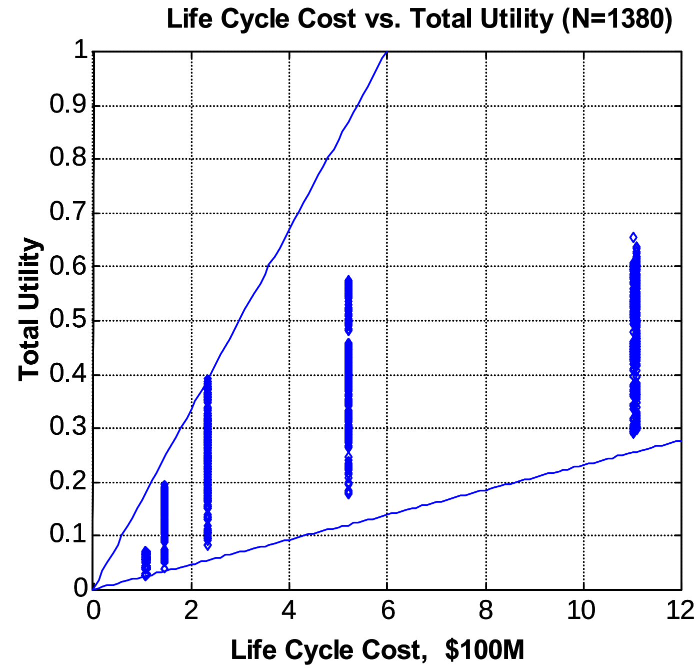
Project 1: A-TOS

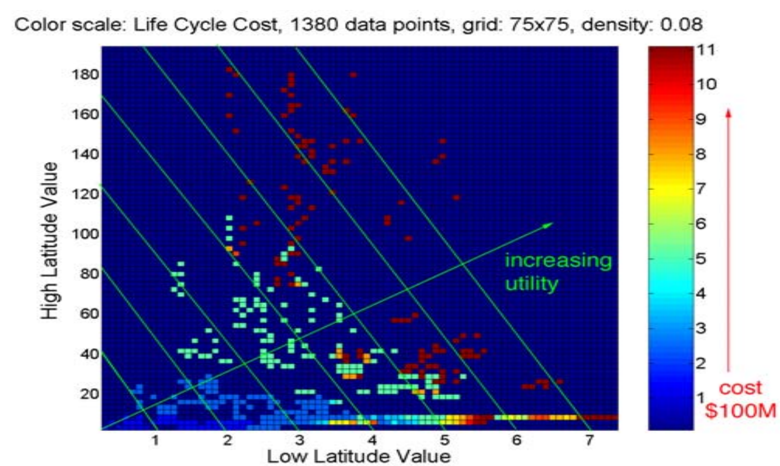


DESIGN VARIABLES

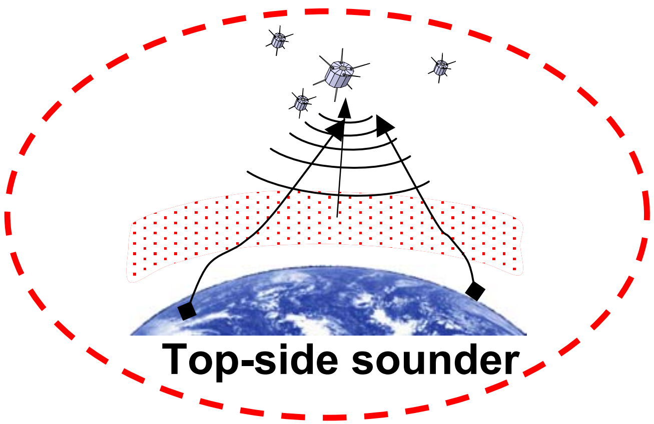
- Bulk Orbit Variables
  - Swarm inclination — 63.4°
  - Swarm perigee altitude — 200 – 800 km
  - Swarm apogee altitude — 200 – 800 km
  - Swarm argument of perigee — 0°
  - Number of orbit planes — 1
  - Swarms per plane — 1
- Swarm Orbit Variables
  - Subsats per swarm — 1 – 26
  - Number of subplanes in each swarm — 1 – 2
  - Number of suborbits in each subplane — 1 – 4
  - Yaw angle of subplanes (a vector) — ±60°
  - Maximum satellite separation — 1 m – 200 km
- Non-orbit Variables
  - Mothership — (yes/no)

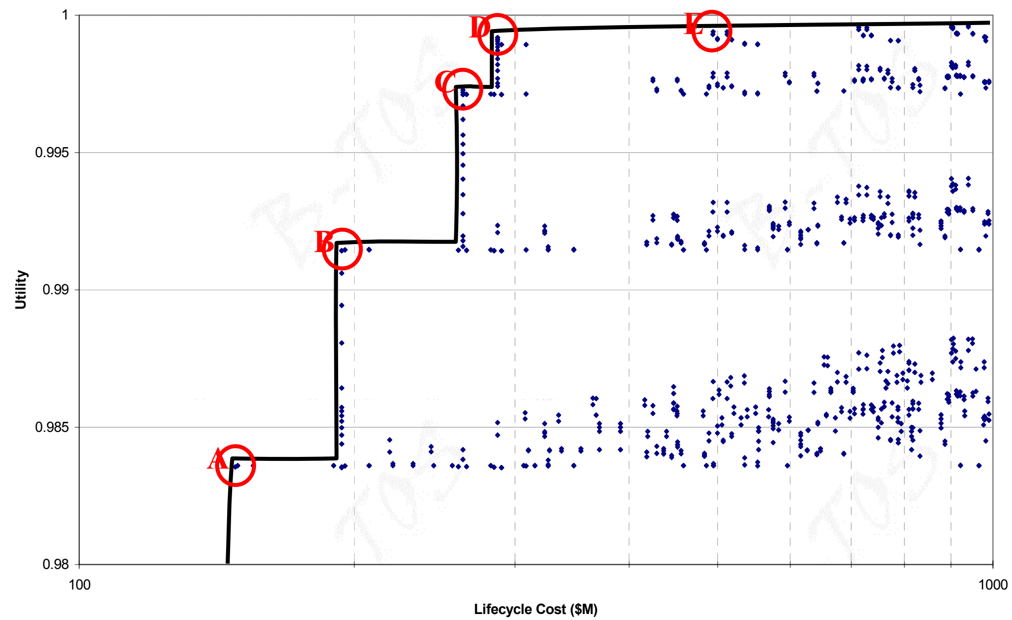
Number of Architectures Explored: 1380





Project 2: B-TOS

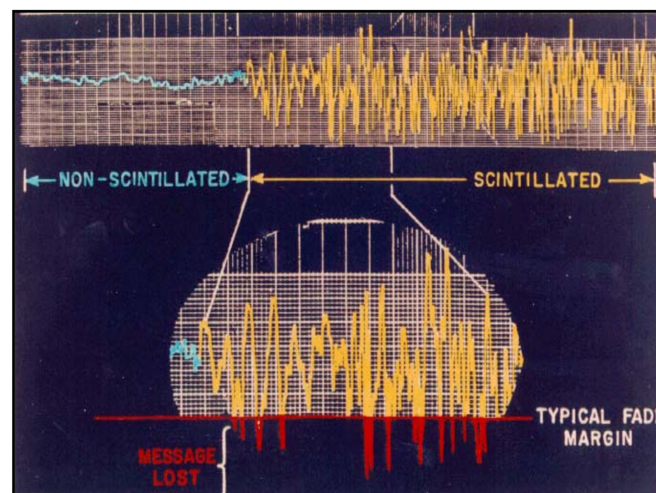




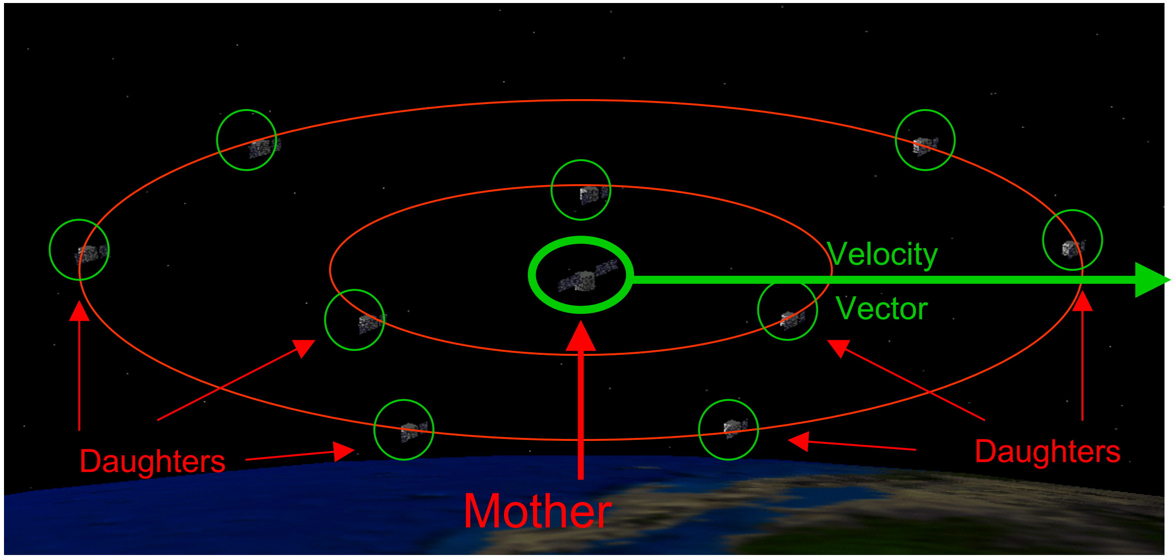
DESIGN VARIABLES

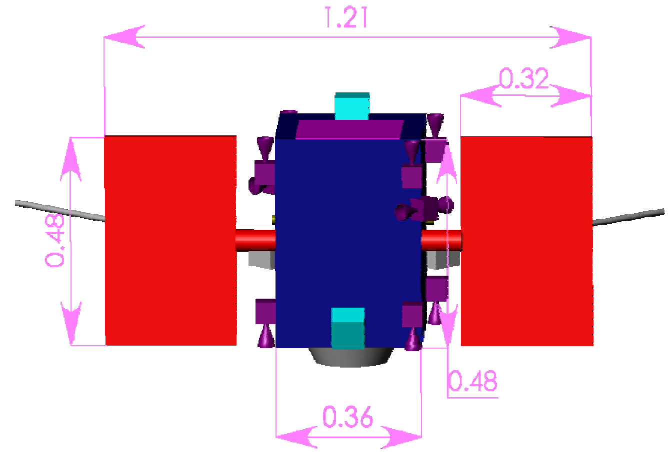
- Large Scale Arch
  - Circular orbit altitude (km) — 1100, 1300
  - Number of Planes — 1, 2, 3, 4, 5
- Swarm Arch
  - Number of Swarms/Plane — 1, 2, 3, 4, 5
  - Number of Satellites/Swarm — 4, 7, 10, 13
  - Radius of Swarm (km) — 0.18, 1.5, 8.75, 50
- Vehicle Arch
  - 5 Configuration Studies — Trades payload, communication, and processing capability

Number of Architectures Explored: 4033

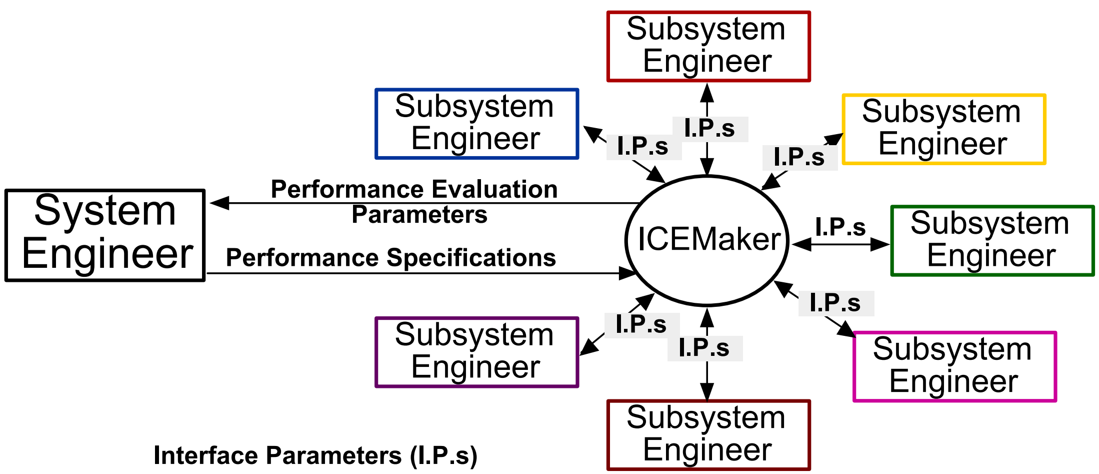


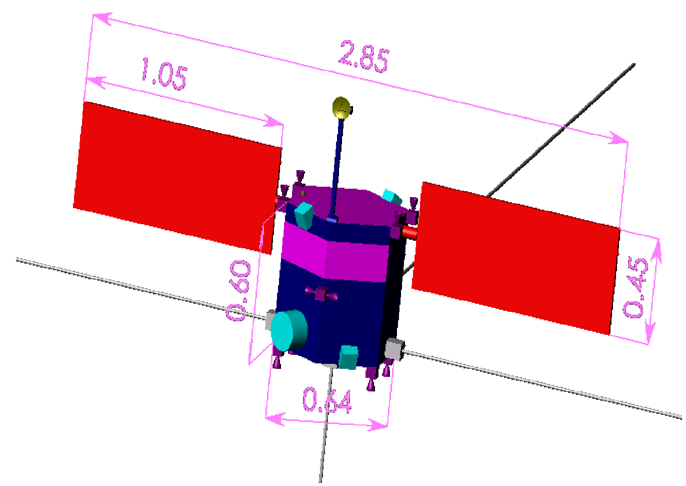
Project 3: C-TOS





All dimensions in meters

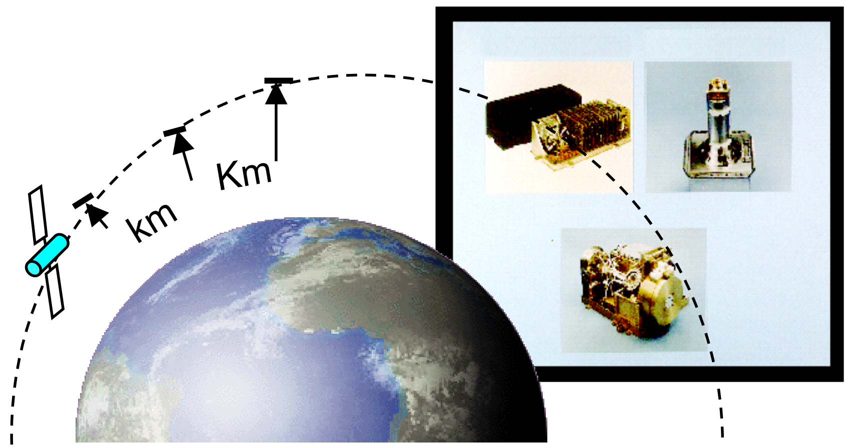


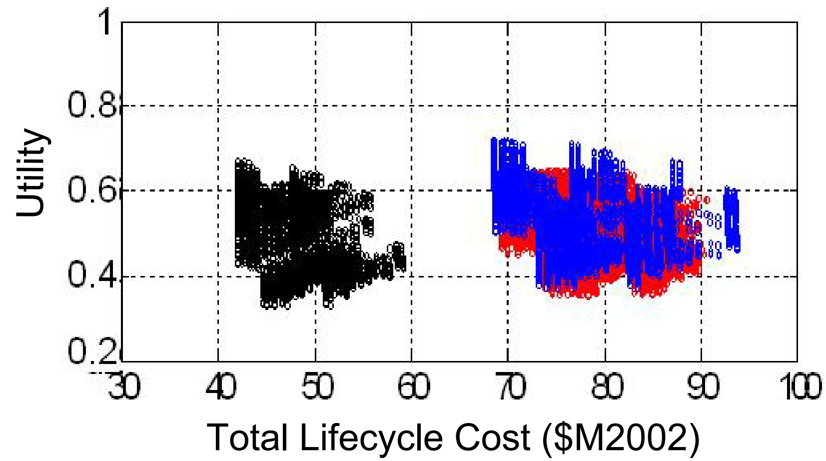


Number of Architectures Explored: 1

All dimensions in meters

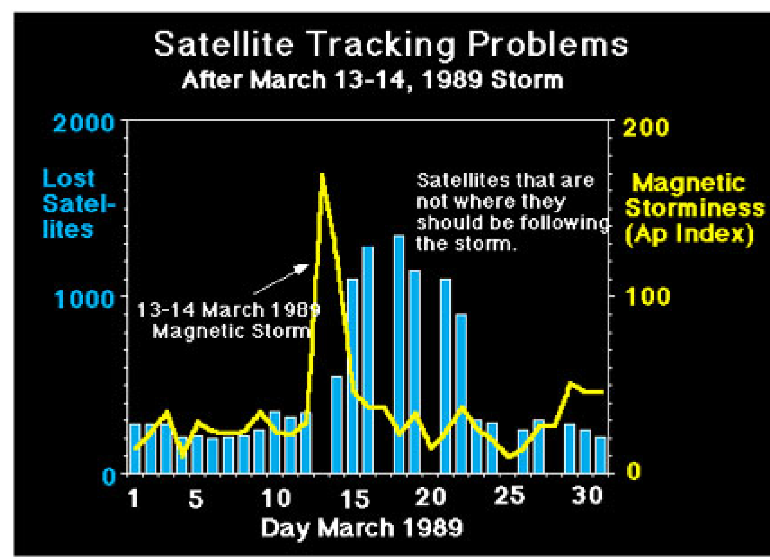
Project 4: X-TOS





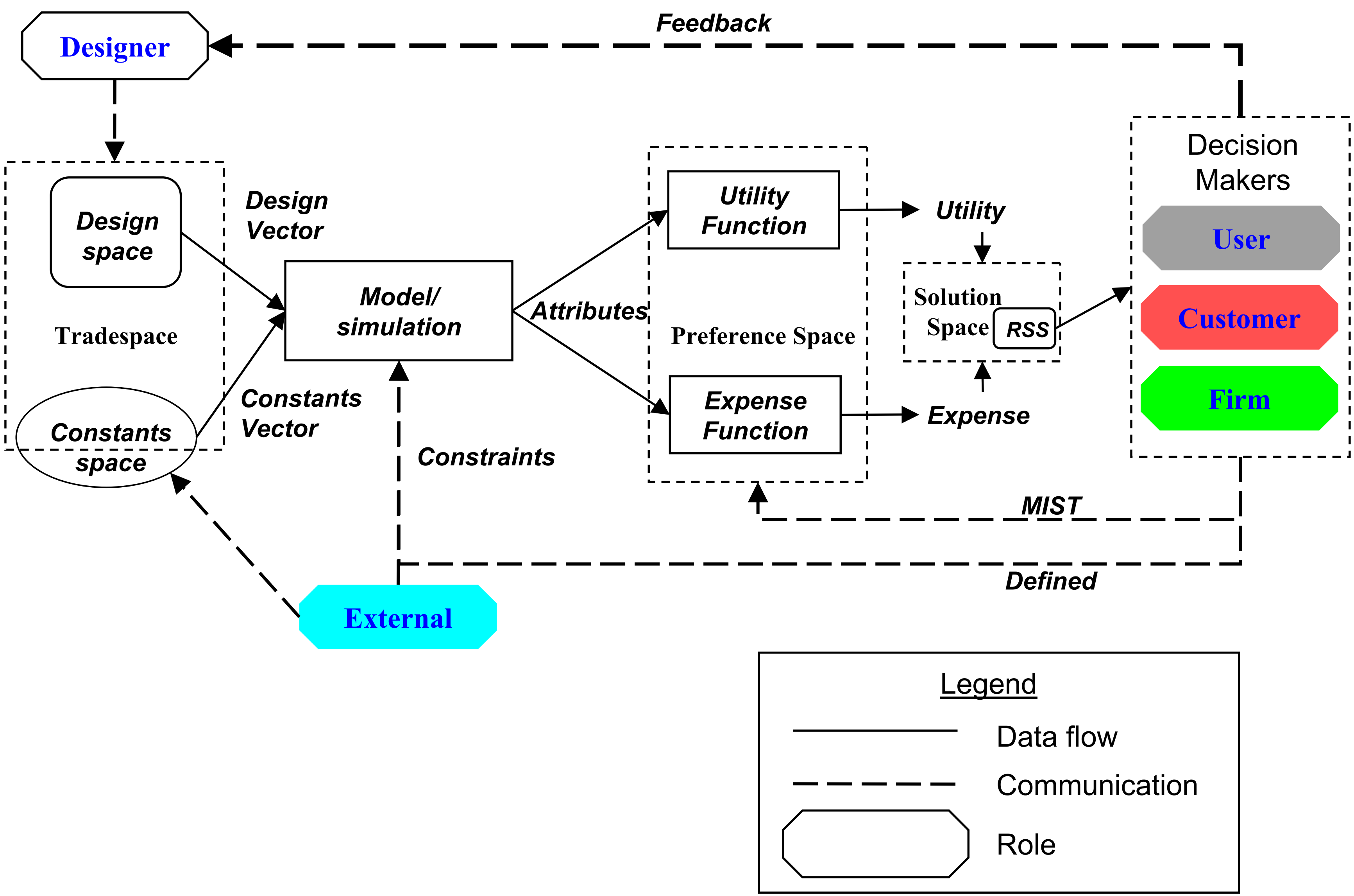
DESIGN VARIABLES

- Mission Scenarios
  - Single satellite, single launch
  - Two satellites, sequential launch
  - Two satellites, parallel
- Orbital Parameters
  - Apogee altitude (km) 150-1100
  - Perigee altitude (km) 150-1100
  - Orbit inclination 0, 30, 60, 90
- Physical Spacecraft Parameters
  - Antenna gain
  - communication architecture
  - propulsion type
  - power type
  - delta_v



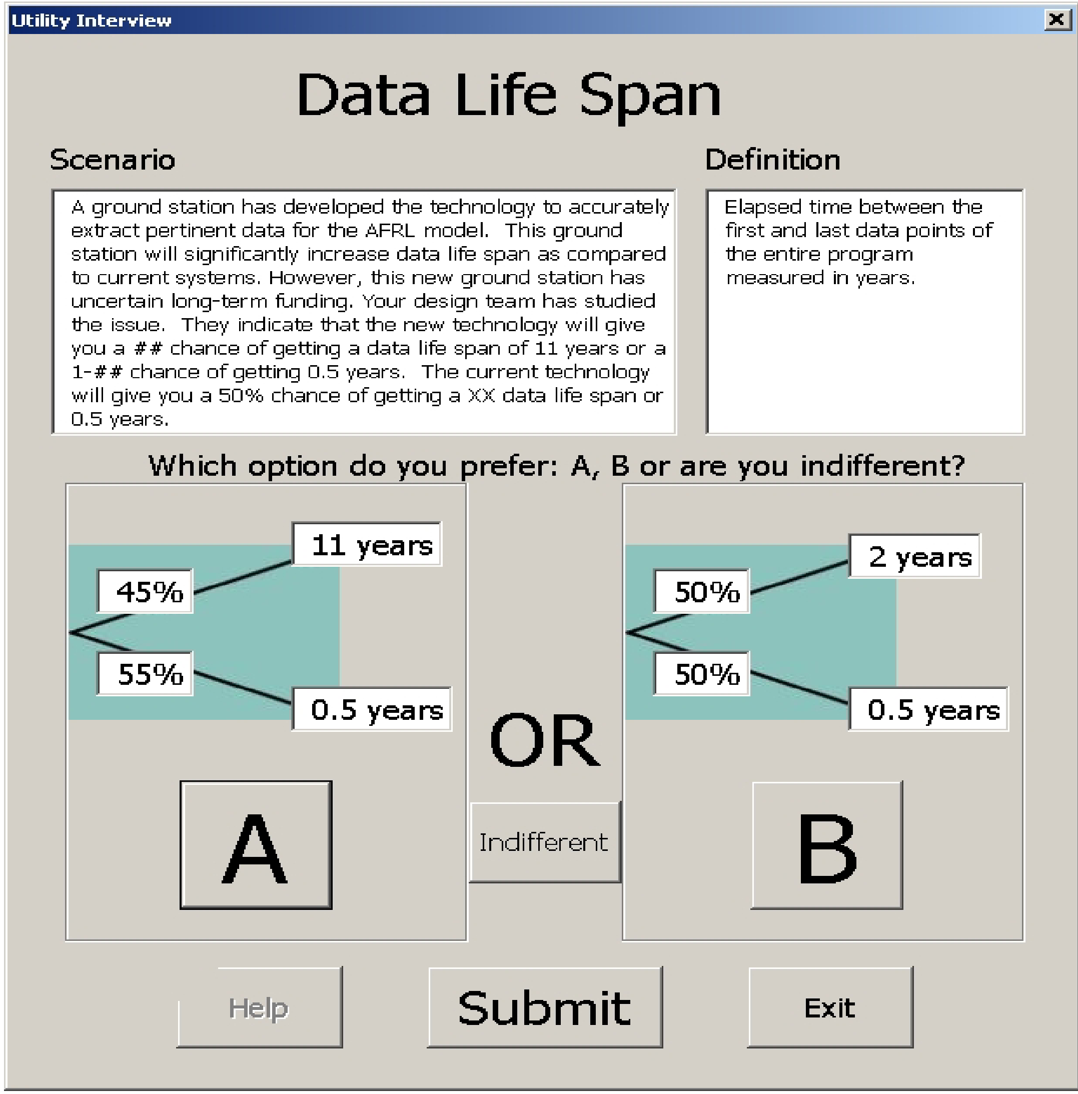
Number of Architectures Explored: 50488

MATE Simulation Flow



Approach to Determining Utility

- Attributes framed by "scenarios"—meant to take each attribute in isolation
- MIST uses "lottery equivalent probability" to create a curve
- User first rates each attribute individually, then balances each against the others



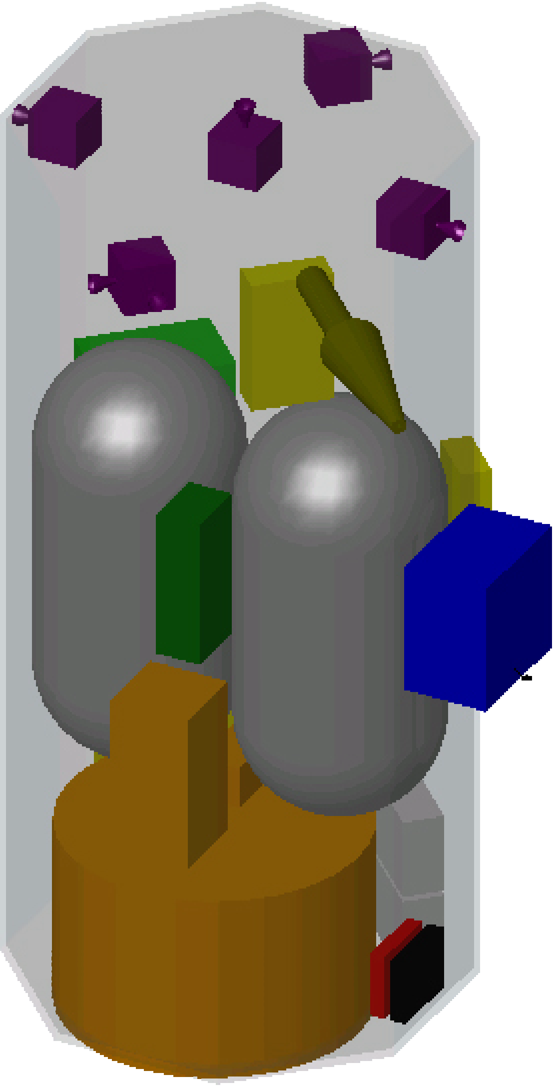
MIST Short-term benefits

- Faster, automated interview process makes more frequent interviews possible (~couple hours/interview)
- Data collected, stored and immediately accessible
- Design history and rationale for attribute definition captured
- Utility functions generated immediately: allows for re-questioning for any ambiguous or inconsistent answers
- Potential for analysis tools to understand relations between multiple stakeholders and multiple projects.

Evolving project will continue to have incremental value at each stage

X-TOS Baseline Design

- Est. Cost: $71.7 M
- USER Utility: 0.611 (0.705*)
- CUST Utility: 0.656 (0.678*)
- Wet Mass: 449.6 kg
- Dry Mass: 188.9 kg
- Lifetime: 0.534 years
- Orbit: 185 km circular
- LV: Minotaur



* Denotes "Original" User Utility

SSPARC

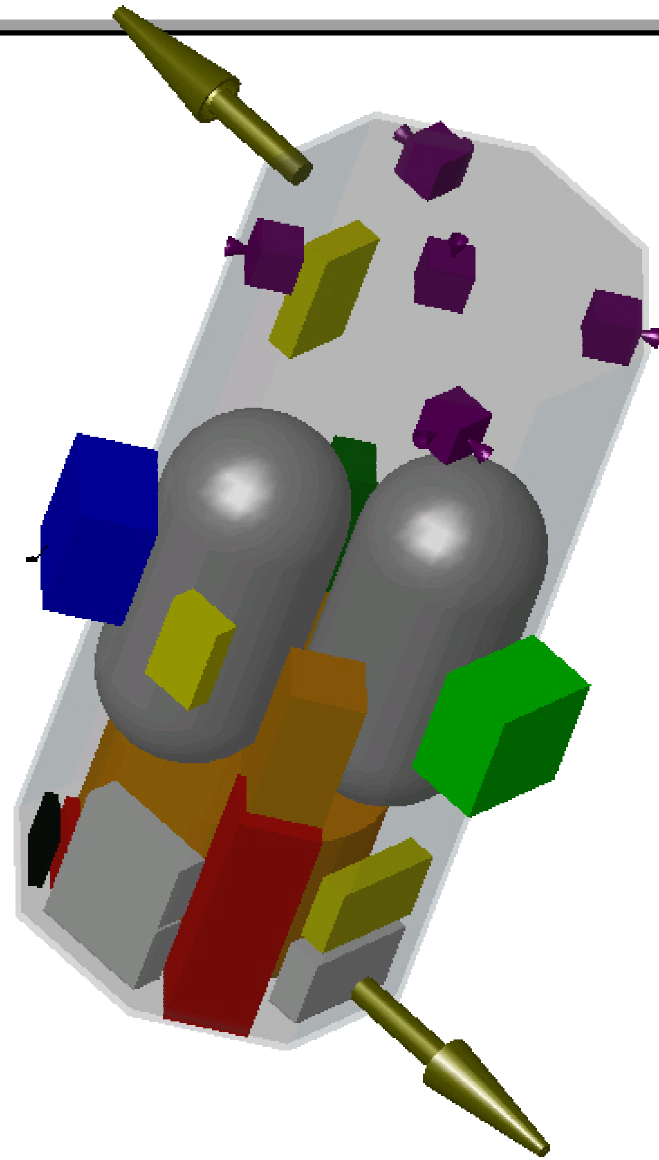
X-TOS Baseline Attributes

Attribute	Value	Units
Lifespan	0.52	years
Latitude Diversity	180	degrees
Equator Time	5.4	hours/day
Latency	1.14	minutes
Altitude	185	km
SSM Cost to IOC	66.6	$M 2002

Decision Maker	Original Prefs	Revised Prefs
USER	0.705	0.611
CUSTOMER	0.686	0.663

X-TOS Last Design

- Est. Cost: $75.0 M
- USER Utility: 0.556 (0.590*)
- CUST Utility: 0.585 (0.640*)
- Wet Mass: 324.3 kg
- Dry Mass: 205.5 kg
- Lifetime: 2.204 years
- Orbit: 300 km circular
- LV: Minotaur



* Denotes "Original" User Utility

X-TOS Last Design Attributes

Attribute	Value	Units
Lifespan	2.2	years
Latitude Diversity	180	degrees
Equator Time	5.4	hours/day
Latency	1.14	minutes
Altitude	300	km
SSM Cost to IOC	69.7	$M 2002

Decision Maker	Original Prefs	Revised Prefs
USER	0.590	0.556
CUSTOMER	0.640	0.585